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NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

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THE STRESS AND TEMPERATURE DEPENDENCE OF
CREEP IN AN AL-2.0WT%LI ALLOY

by

Earl F. Goodson
December 1989

Thesis Advisor:
Co-Advisor:

Terry R. McNelley
Alan G. Fox

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The Stress and Temperature Dependence of Creep in an Al-2.0wt%Li
Alloy

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the requirements
for the degree of

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ABSTRACT

The effect of stress and temperature on the creep behavior of an Al-2.0wt%Li alloy was investigated in the temperature range from 300 to 500°C. This temperature interval corresponds to a solid solution of Li in Al. Experimental results indicate that Al-2.0wt%Li behaves as a pure metal class alloy (class II). This is demonstrated by several creep characteristics including the value of the stress exponent ($n \sim 5$), the shape of the creep curve, and the nature of the creep transient after a temperature change. However, anomalous behavior of the activation energy was observed. Activation energies up to 55 kcal/mole, decreasing to approximately 33 kcal/mole at higher temperatures, were observed by the temperature cycling technique.

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I. INTRODUCTION

Both the blacksmiths of old and today's metallurgists have long recognized that small changes to processing variables or to alloy compositions can create widely varying effects on the mechanical properties of the resulting metal. Metallurgists today attribute these effects on the mechanical properties to changes in the microstructure. Now, metallurgists must explore and exploit these effects to meet the demands of today's rapidly evolving materials needs.

From Italy's Da Vinci to America's Wright brothers, aviation has always been at the forefront of technology. Military specifications dictate that putting more payload in the air is the overwhelming factor in design. Aluminum alloys are the predominant materials of airframe construction because of their high strength-to-weight ratio when used as beam structures and aircraft skin. Criteria used to evaluate metals for aerospace applications begin with relative strength and density. However, some components must withstand necessarily high temperatures as well as maintain good strength characteristics. Other important criteria include resistance to cyclic fatigue, corrosion resistance, weldability and good appearance.

Many materials have adequately met these criteria and are in wide use today. Factors which spur continued research in high strength, temperature resistant Aluminum alloys are cost of materials, as well as fabrication and lifecycle costs. When Li is added to Al it forms an alloy with a lower density and a higher modulus of elasticity than pure Al. Yet Al-Li alloys without other alloying elements are not widely used commercially due to poor mechanical properties. When other alloying elements are added to Al-Li systems, the mechanical

properties can be improved dramatically. At ambient temperatures, the mechanical properties of Al-Li alloys are well known. These include factors such as high strength-to-weight and stiffness-to-weight ratios, and good toughness and cyclic fatigue characteristics. However, very little information exists on the high temperature behavior of the Al-Li system. Thus, limits on elevated temperature exposure of these alloys have yet to be determined. Therefore, it is the main thrust of this investigation to expand the body of data on an Al-2.0wt%Li alloy in terms of the stress and temperature dependence of its creep behavior, as well as to investigate the activation energies for creep in the temperature range 300 to 500°C.

II. BACKGROUND

A. CREEP OF SOLID-SOLUTION ALLOYS

This research considered the constant stress creep behavior of Al-2.0wt%Li in the temperature range from 300 to 500°C. The solvus temperature for this alloy is ~ 360°C (see Figure 1). Thus at 300 and 350°C effects may arise due to precipitation. From 400°C upwards, the effects of solid solution strengthening alone, without influence from precipitation, will be observed.

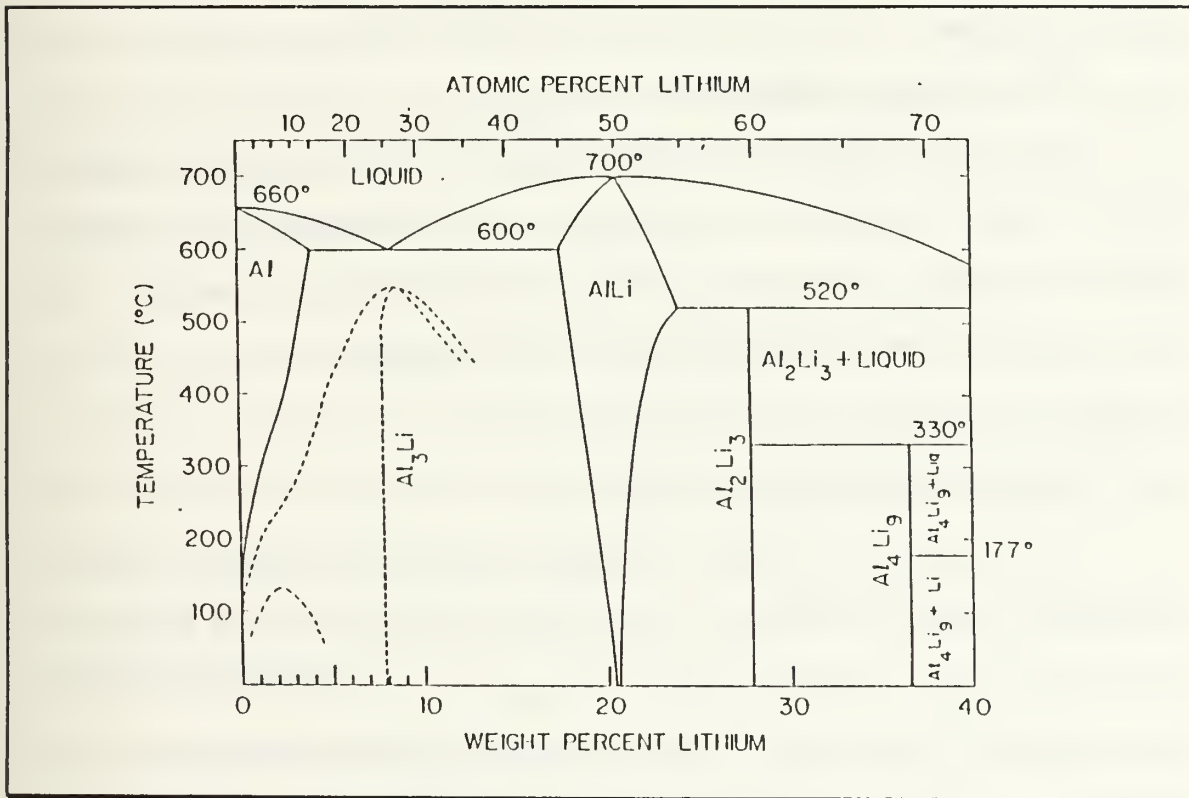


Figure 1. Al-Li Phase Diagram

The creep response of solid solutions has been classified into two categories based on the premise that dislocation motion occurs through sequential glide and climb processes [Ref. 1].

1. Class I Solid Solutions

The first category commonly referred to as class I or alloy class, exhibits dislocation glide as the rate-controlling process during deformation due to solute drag on the moving dislocations. Class I alloys commonly exhibit a stress exponent, n ($= d \ln \sigma / d \ln \dot{\epsilon}$), of about 3, a brief primary stage of creep and random distribution of dislocations. The activation energy is equal to that for solute diffusion.

2. Class II Solid Solutions

The second category is called class II or pure metal class, where dislocation climb becomes rate-controlling. Class II alloys exhibit a stress exponent, n , close to 5, extensive primary creep and subgrain formation. The activation energy is essentially equal to that for self-diffusion.

B. STRUCTURE OF AL-LI ALLOYS

1. Effect of Li Addition in Al

As an addition to Al alloys, Li offers a significant decrease in density and increase in modulus of elasticity. Li has a high solubility in Al (5.2%) in the binary Al-Li system. Greatly improved strengths result from the δ' (Al_3Li phase) precipitation during age hardening. Also, each percent of Li added to Al reduces the density of the alloy by 3% and increases the modulus of elasticity by 6%, up to 4 % Li additions.

The role of Li increasing the modulus of elasticity of Al has been addressed recently in a paper by Fox and Fisher on a study of 1.33 and 2.14wt%

Lithium additions to Al. The Li addition in Al results in an increase in the electron charge density between Al and Li atoms. Accordingly, this increase in charge density results in an increased average force of attraction between the atoms and thus an increased modulus of elasticity.[Ref. 2]

2. Ordering in the Al-Li Matrix

Radmilovic, Fox and Thomas contend that ordering exists within the range of the solid solution and not only in the temperature region below the solvus. This was based on the observation of superlattice reflections and no discernable δ' particles irrespective of prior solution treatment temperature or quench medium employed following solution treatment. The ordered alloy apparently decomposes into a modulated order/disorder structure by a spinodal mechanism with increased Li content in the ordered regions until such regions coarsened into discrete δ' particles.[Ref. 3]

The increased modulus and the presence of ordering in the solid solution are evidence that Al and Li atoms tend to bond readily. The temperature dependence of such bonding has not been addressed. It has been shown, however, that both the modulus of elasticity and the stacking fault energy influence the creep behavior of materials, hence it is likely that the creep response of Al-Li alloys may be influenced by Li addition through these material parameters [Ref. 1].

C. THE MECHANISM OF CREEP

1. Interaction of Dislocations and Solute Atoms

A dislocation has a stress field associated with it. Solute atoms, because their sizes are either too small or too large in relation to the solvent atom size, are also centers of elastic strain. Consequently, the stress fields from these

sources can interact and can mutually exert force. This is an elastic interaction due to misfit.

The interaction of the solute atoms and edge dislocations leads to a migration of solute atoms to the dislocation where they form an atmosphere around it. This solute atmosphere, called the Cottrell atmosphere, has the effect of locking the dislocation. This makes it necessary to apply additional force to free the dislocation from the atmosphere.[Ref. 4]

Li atoms are very close to the same size as Al atoms. However, even when the size difference is zero, a contribution to the binding energy between the solute and the dislocation can result due to the difference in modulus between the two. The solute atom behaves as an elastic heterogeneity in the dislocation strain field. If the solute is softer (i.e. smaller shear modulus) than the matrix, the energy of the strain field of the dislocation can be reduced by distortion of solute. This means that the energy will be negative and thus there will be an attraction between the solute and the matrix. For a solute that is harder than the matrix, there will be a force of repulsion between the two.[Ref. 4]

At high temperatures ($> 0.5 T_m$), the mobility of the solute atoms will be much greater than that of the dislocation, with the result that they will not restrict the dislocation motion. In the range of temperature where solute atoms and dislocations are equally mobile, there are strong interactions with dislocations.[Ref. 4]

The movement of dislocations will result in disordering of ordered regions in a partially ordered alloy. This disruption would cause an increase in the energy of the material and requires additional work to be done. Mechanical properties thus are altered when materials have an ordered structure. Fully

ordered alloys may deform by means of the movement of superlattice dislocations at rather low stresses. However, the super dislocations (i.e. closely spaced pairs of unit dislocations bound together by an antiphase boundary) must move as pairs in order to maintain the ordered structure. This makes cross-slip and climb more difficult. Long-range order thus leads to high rates of strain-hardening and frequently to brittle fracture as well as high-temperature creep resistance.[Ref. 4]

2. Creep Rate Dependence on Temperature

Creep is a thermally activated process. Thus, the creep rate, $\dot{\epsilon}_{\min}$, can be described by an Arrhenius type of relation:

$$\dot{\epsilon}_{\min} \propto \exp \left(\frac{-Q_c}{RT} \right) \quad (1)$$

where Q_c is the activation energy for creep, R is the gas constant, and T is the absolute temperature. This has been demonstrated by several experiments.[e.g. Ref. 1]

3. Creep Rate Dependence on Diffusion

If the creep rate is dependent on dislocation climb or upon the motion of jogged screw dislocations, then the steady state creep rate, $\dot{\epsilon}_{\min}$, should be proportional to an appropriate diffusion coefficient, D :

$$\dot{\epsilon}_{\min} \propto D \quad (2)$$

and there is ample evidence for the correlation of $\dot{\epsilon}_{\min}$ and D . For example, the steady-state creep rate stress data at various temperatures for a given metal can be made to virtually coincide if the creep rate is first divided by the diffusion coefficient for the appropriate temperature and then plotted against stress. Since the creep rate is proportional to the diffusion coefficient, it is logical that the

activation energy for creep of pure metals should be about equal the activation energy for self diffusion.[Ref. 1]

4. Creep Rate Dependence on Stress

Sherby and Burke [Ref. 1] note that for low and intermediate stresses, the relationship between the creep strain rate and stress (at constant temperature) can be described by the power-law relation:

$$\dot{\epsilon}_{\min} \propto \sigma^n \quad (3)$$

where σ is the stress. If creep can occur by several different independent processes, the fastest of these will be rate-controlling. Thus, the mechanism of creep at very low stresses (range I) can be associated with the creep law:

$$\dot{\epsilon}_{\min} \propto \sigma^1 \quad (4)$$

where n equals 1, since this creep process yields a more rapid creep rate than the process responsible for the intermediate stress (range II) where:

$$\dot{\epsilon}_{\min} \propto \sigma^n \quad (5)$$

and where the value of the stress exponent, n , is greater than 1 [Ref 1]. With increasing stress, it is expected that a transition in creep mechanisms will occur as the rate of range II processes increases more rapidly with stress than the rate of range I processes.

5. Class I Alloys and Their Creep Rate

Sherby and Burke [Ref. 1: p. 341] note that creep of solid solution alloys between $\dot{\epsilon}/D$ values ranging typically from 10^2 to 10^9 cm^{-2} can be divided into two categories. Class I alloys are first and their strain rate is proportional to the cube of the modulus-normalized stress:

$$\dot{\epsilon}_{\min} = B D_s \left(\frac{\sigma}{E} \right)^3 \quad (6)$$

where $\dot{\epsilon}_{\min}$ is the strain rate, B is a physical constant, D_s is the diffusion coefficient for the solute, σ is the true stress, E is the elastic modulus and n is equal to three. Dislocation glide is the mechanism for creep where the velocity of the dislocation motion is determined by the amount of friction that the solute atoms generate to oppose the glide motion. The activation energy for creep would be the activation energy for diffusion of the Li solute.

6. Class II Alloys and Their Creep Rate

Class II alloys are the second classification and their strain rate, $\dot{\epsilon}_{\min}$, is proportional to the cube of the stacking fault energy, $(\gamma)^3$, to the modulus-normalized stress raised to the fifth power, $(\frac{\sigma}{E})^5$ and to the self-diffusion coefficient, D_1 :

$$\dot{\epsilon}_{\min} = A (\gamma)^3 \left(\frac{\sigma}{E} \right)^5 D_1 \quad (7)$$

where A is a material constant, R is the gas constant, and n is equal to five. The mechanism of creep in this class is dislocation climb, the rate of which is also affected by subgrain size. Class II alloys exhibit a distinct primary creep stage, similar to pure metals, and the activation energy for creep can be anticipated to be the same as the activation energy for self-diffusion. On the basis of increased modulus alone, one could anticipate that the strain rate of the alloy would be slower than that of Al for either class I or class II alloys.

D. OTHER EFFECTS ON THE ACTIVATION ENERGY

The activation energy for a given metal can be calculated if the creep rate is known at two temperatures:

$$Q_c = -R \left(\frac{\Delta \log \dot{\epsilon}}{\Delta \frac{1}{T}} \right) |_{\sigma, \epsilon} \quad (8)$$

Earlier, it was noted that the activation energy for creep was about equal to the activation energy for self-diffusion. If, however, the modulus were to be strongly temperature dependent, the activation energy for creep would not be exactly equal to the activation energy for self-diffusion. Similarly, the stacking fault energy may vary with temperature. The influence of such temperature dependent factors can be shown with the aid of equations 7 and 8:

$$Q_c = -R \left(\frac{\Delta \log \dot{\epsilon}}{\Delta \frac{1}{T}} \right)_{\sigma, \epsilon} = -R \frac{\partial \ln D}{\partial \frac{1}{T}} \Big|_{\sigma, \epsilon} + 5R \frac{\partial \ln E}{\partial \frac{1}{T}} \Big|_{\sigma, \epsilon} - 3R \frac{\partial \ln \gamma}{\partial \frac{1}{T}} \Big|_{\sigma, \epsilon} \quad (9)$$

The term $-R \partial \ln D / \partial (1/T)$ is simply equal to the activation energy for self-diffusion. So, equation 9 becomes:

$$Q_c = Q_d + 5R \frac{\partial \ln E}{\partial \frac{1}{T}} - 3R \frac{\partial \ln \gamma}{\partial \frac{1}{T}} \quad (10).$$

If E and γ do not change much with temperature, then Q_c will effectively equal Q_d . However, if E and γ are strongly temperature dependent then Q_c would differ from Q_d .

This, in fact was found to be the case, as experimentally determined values of Q_c were observed to be greater than known values of Q_d for pure Al in the temperature range of 300 to 470°C.

E. PREVIOUS RESEARCH AT NPS

Anomously high activation energies were reported by Taylor [Ref. 5] in his study of Al-0.5wt%Li and Al-1.0wt%Li, as well as by Ellison [Ref. 6] in his study of Al-2.0wt%Li. These results were attributed to the alloy's temperature dependence of the modulus and the stacking fault energy relative to pure Al. These results represent the initial point where this study of the creep behavior and of the activation energy for Al-2.0wt%Li commences.

III. EXPERIMENTAL PROCEDURE

A. CASTING AND SECTIONING

A Al-2.0wt%Li casting, number NPGS13 and manufactured utilizing 99.99 percent pure Aluminum alloyed with 99.90 percent pure Lithium, was received from the Naval Surface Weapons Center (NSWC) in White Oak, Maryland. The casting was in the form of a tapered cylindrical ingot 200 mm (8.0 in) in length and approximately 76 mm (3.0 in) in diameter. The casting was sectioned into billets for subsequent solution treatment and processing. The traverse sections were 25 mm (1.0 in) thick and 76 mm (3.0 in) in diameter.

B. THERMOMECHANICAL PROCESSING

Solution treatment was conducted at 540°C for 12 hours with a subsequent water quench to room temperature. A Lindburg Type B-6 heavy duty furnace was used for homogenization. For rolling, the homogenized billet was placed in a Blue M furnace, Model 8655f-3, for 5 minutes reheating at temperatures between 400°C and 450°C prior to each rolling pass. A massive steel plate was located on the floor of the furnace to act as a heat capacitor in order to maintain a stable annealing temperature. Care was taken to commence the 5 minute anneal "clock" once the temperature of the billet was above 400°C. The last rolling pass was followed by cold water quenching to room temperature. The TMP is schematically represented in Figure 2.

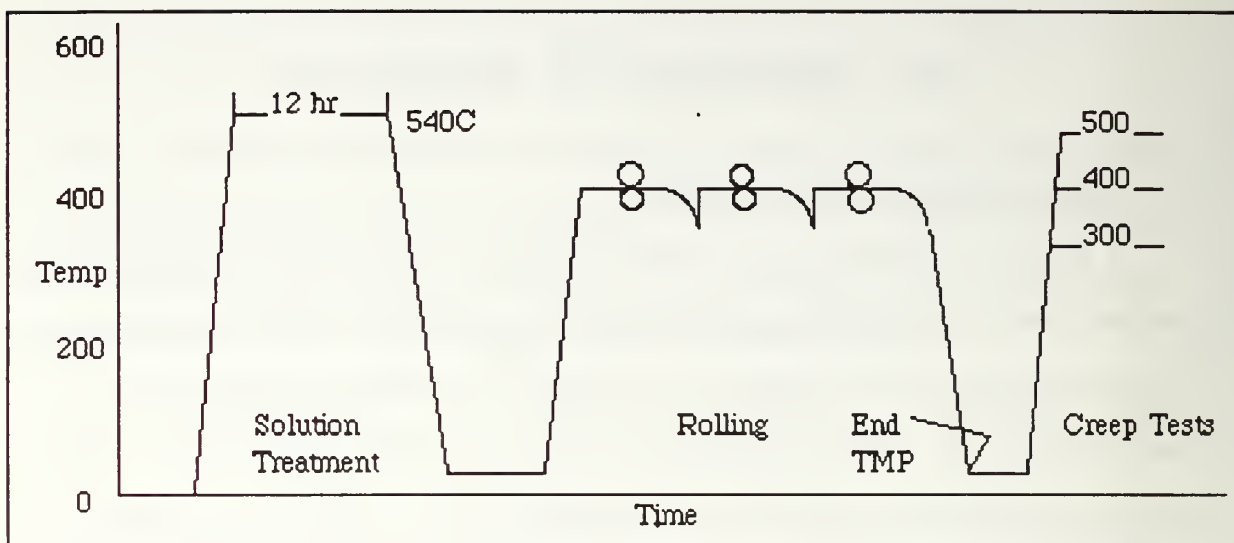


Figure 2. TMP for Samples

Billets were rolled in a Fenn Laboratory Rolling Mill using the reduction scheme shown in Table 1. By turning the screw down wheels the number of turns indicated (second column) to the setting shown (third column), then the mill gap indicated (fourth column) would result in the amount of strain per pass shown (last column).

The resulting rolled strip, nominally 2 mm (0.08 in) in thickness, was machined to dimensions for tensile testing, see Figure 3. The rolled strip was first cut by band saw into rectangular blanks and machined into reduced gauge section, sheet-type, tensile specimens with the long axis parallel to the rolling direction. A special holding device was fabricated to secure the samples during machining due to the extreme softness and ductility of the material. Five specimens were machined at one time. The finished samples were examined for defects and all machining burrs were carefully removed with a jeweler's file.

Prior to testing, all samples received a heat treatment of 15 minutes at 500°C to provide a fully annealed microstructure.

Table 1. ROLLING SCHEDULE

ROLL #	ROLL CHANGE (0.08 in + 0.01 in)	MILL SETTING (right/left)	MILL GAP (in)	% STRAIN (per pass)
open	+(12 + 4)	0/0	0.94	--
1	-(2 + 0)	0/0	0.84	10.4
2	-(1 + 2)	6/6	0.74	12.0
3	-(1 + 2)	4/4	0.64	13.5
4	-(1 + 2)	2/2	0.54	15.6
5	-(1 + 2)	0/0	0.44	18.5
6	-(1 + 2)	6/6	0.34	22.7
7	-(1 + 2)	4/4	0.24	29.4
8	-(0 + 6)	6/6	0.18	25.0
9	-(0 + 5)	1/1	0.13	27.7
10	-(0 + 4)	5/5	0.09	30.7
11	-(0 + 3)	2/2	0.06	33.3
12	-(0 + 1.3)	0.7/0.7	0.047	21.7

C CONSTANT EXTENSION RATE TESTS

Constant extension rate tensile tests were performed on an Instron TM-S-L Table Model Universal Testing Machine with a 1,000-pound calibrated load cell.

The tensile testing temperature was maintained by a Marshall tubular furnace in combination with a Lindburg Model 59344 temperature controller.

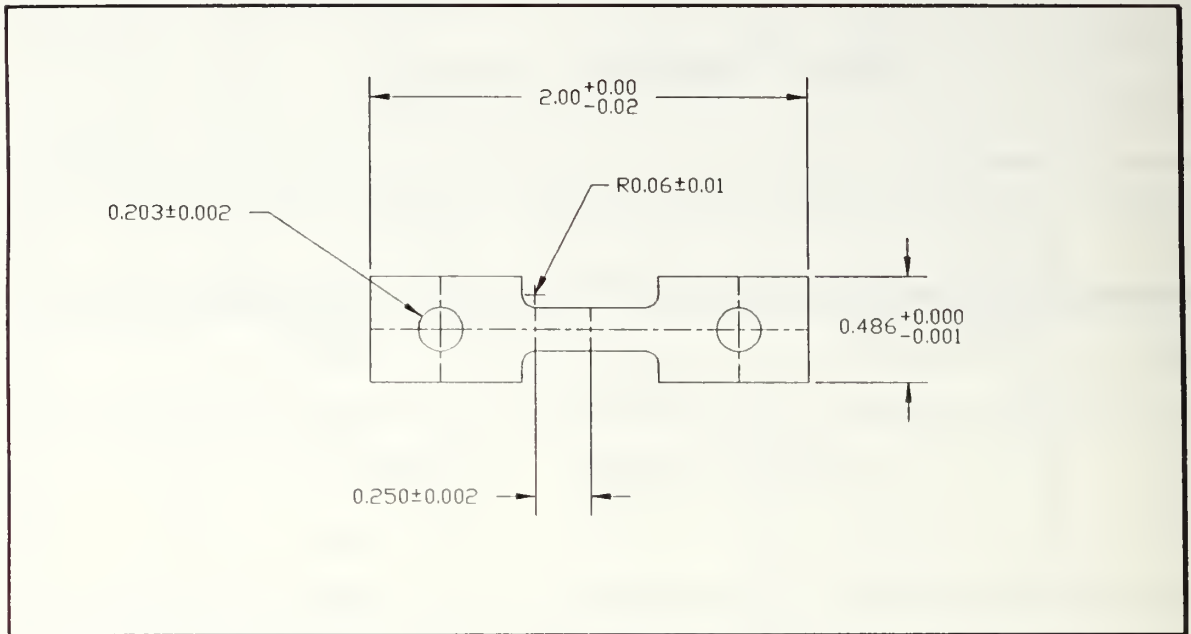


Figure 3. Tensile Test Specimen Drawing

Special self-aligning grips were designed to hold the tensile test specimens (Figure 4)[Ref. 5]. These grips were fabricated of Inconel 625 alloy by Collins Instrument Company, Freeport, Texas, using a wire electro-discharge machining (EMD) process for tolerance control.

Unique features of these grips include a tapered shank leading to a button head which aligns itself by transmitting the load to the grips via the taper. The recessed face of the grips compressively hold the specimen, applying the load to the entire tab, not just the area above the bolt hole.

Once temperature was attained, the furnace was de-energized, lowered, and the grip assembly with the sample installed was inserted into the grip holder

assembly. The furnace was raised, re-energized and allowed again to stabilize for approximately 45 minutes. While the sample and grips were equilibrating, the slack was removed from the load train by a small pre-load in order to prevent slippage in the grips. Since the entire gauge/grip/heater assembly is mounted to the bottom of the crosshead and moves down with the crosshead as the test progresses, the original temperature gradient can be maintained for any extension likely to be encountered with this alloy.

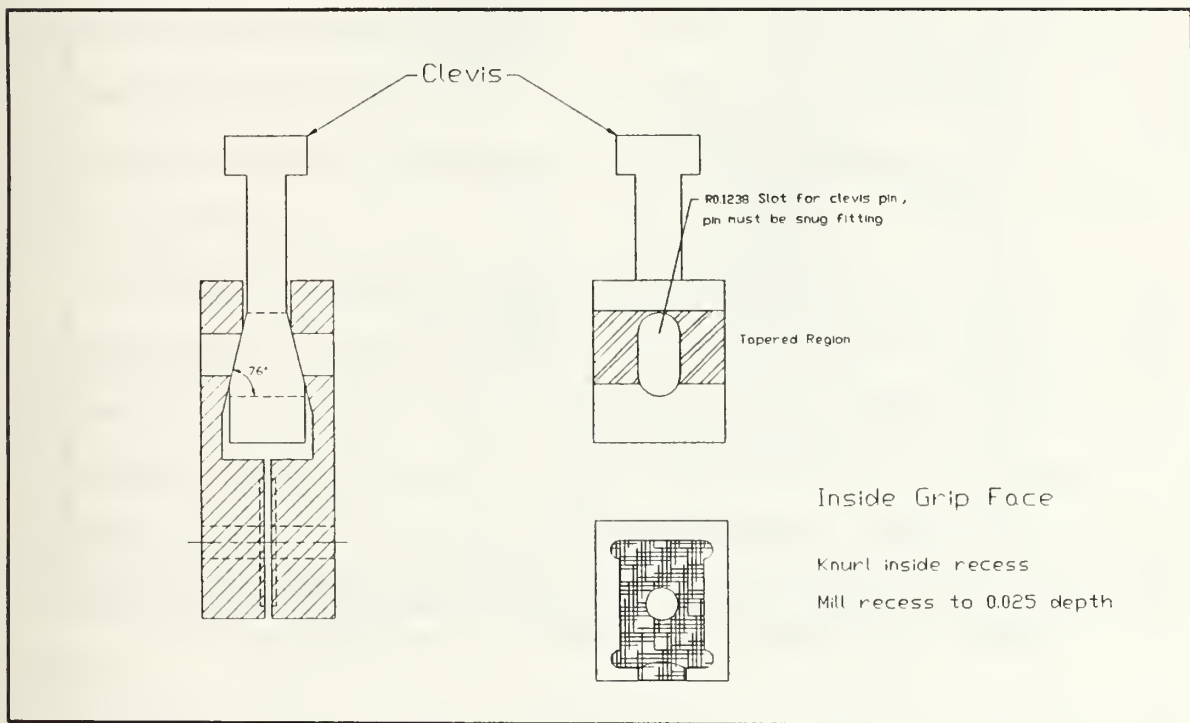


Figure 4. Self-Aligning Grip Assembly

D CONSTANT STRESS TESTS

Constant stress tensile creep tests were conducted on a pair of test machines designed at NPS and were patterned after a machine built by Barrett and later

modified by Matlock at Stanford University [Ref 6]. The constant stress is obtained by means of an Andrade-Chalmers lever arm. The contoured lever rotates as the specimen elongates (Figure 5).

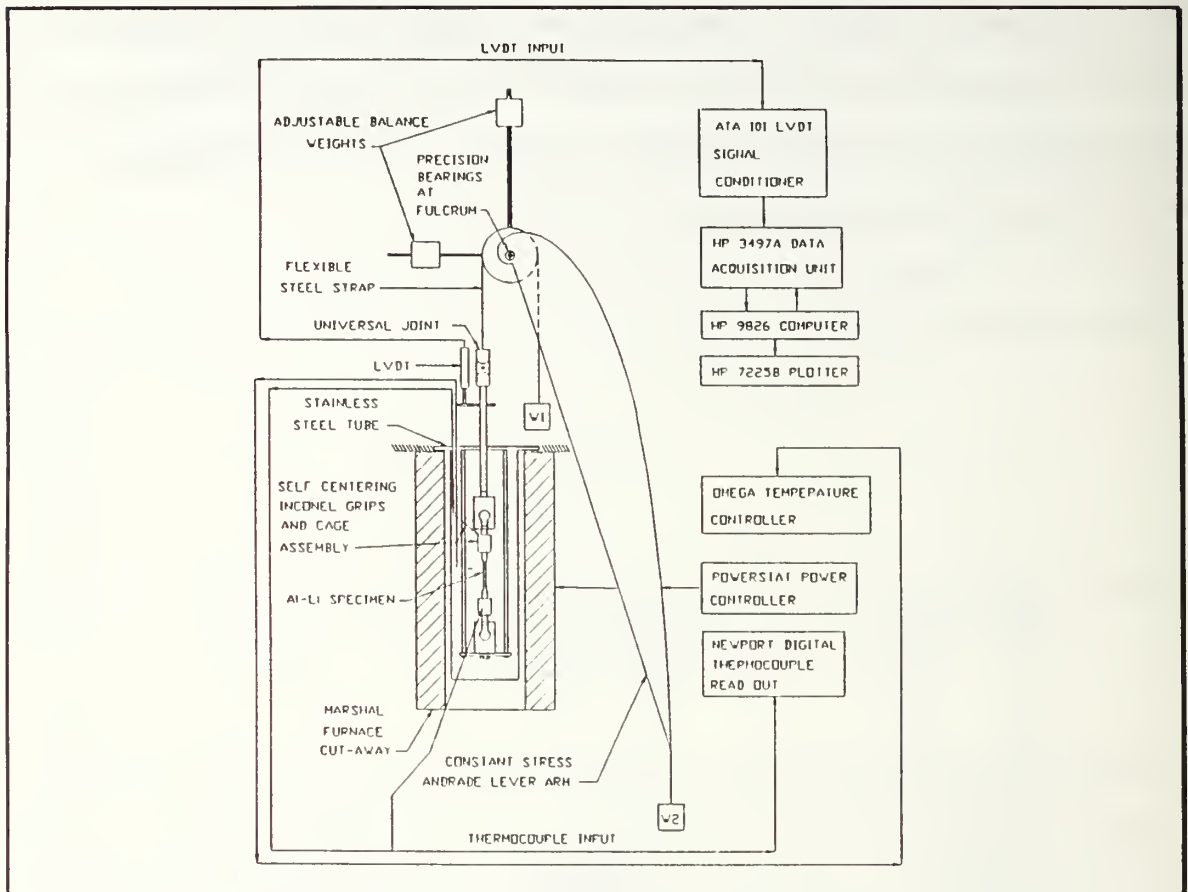


Figure 5. Diagram of Constant Stress Machine

This rotation decreases the moment arm of the applied load as the cross-sectional area of the specimen decreases with elongation, thus maintaining a constant true stress. The design of the arm is based on the assumption that the load train is rigid and the linkage displacement is taken up uniformly. The

machine is capable of transmitting loads between 1.5 and 222.5 Newtons (0.3 to 50 lbs) and at strains as high as 300 percent.

The contour of the lever arm was designed using Autocad in conjunction with the highly accurate graphical technique developed by Coghlan[Ref. 8]. The design used an effective gauge length of 13 mm (0.5 in) with an initial lever arm ratio of 10:1. The lever arm was constructed of 6.4 mm (0.25 in) thick 2024-T6 Aluminum and is attached to a 9.53 mm (0.375 in) diameter shaft rotating on a set of precision bearings. An adjustable counterbalance was affixed to the opposite end of the shaft, balancing the lever arm. This counterbalance in conjunction with another weight attached to the shaft to compensate for the weight of the load train, ensured that the only load sensed by the sample was that of the applied load.

A flexible 0.55 mm (0.02 in) thick steel strap follows the lever arm contour and hangs along the vertical tangent to the lever. A second flexible strap hangs tangent to a two inch radius disc centered at the fulcrum point which transmits the tensile load to the sample via the load train. The entire linkage was calibrated using a 50 lbf capacity interface load cell installed in the load train. The maximum stress variation through 300 percent elongation was 1.4 percent [Ref. 5].

Sample elongation was measured using a Schaevitz linear variable differential transformer (LVDT) with a 1 inch displacement. The core of the LVDT was attached to the upper specimen linkage. The 2.866 mv/v signal output from the LVDT is conditioned by a Schaevitz Model ATA 101 analog transducer amplifier. The amplifier voltage was measured by a Hewlett-Packard

(HP) Model 3497A Data Acquisition Unit controlled by an HP Model 9826 computer.

Marshall tubular furnaces were used for temperature control in conjunction with Eurotherm Model 808 digital temperature controllers. The temperature gradient in the furnaces was controlled and monitored similarly as with the Instron testing. Preheat and sample loading procedures were also similar.

Prior to the temperature stabilizing, the creep test program was started. The LVDT was zeroed (as determined with a digital multi-meter) in parallel with the amplifier (later, this step would be eliminated by a modification in the creep data acquisition program which zeroed the readings artificially). A precalculated weight in a plastic bag was carefully suspended from the lever arm by the flexible strap, and each test was allowed to continue to failure.

1. Features of the Software for the Constant Stress Tests

The software designed to run the creep tests was written in HP Basic 2.0 and featured a user friendly, menu-driven interface, see Appendix G. The software was designed to control two creep machines running simultaneously, and would plot and display on a video monitor the real time engineering strain vs time graphs for simultaneous tests. The algorithm was written to sample 5000 voltage and time data pairs for each test and then convert the voltage to engineering strain using 1volt per 20% strain. Once the test was completed the menu gave the user the choice of plotting either true/engineering strain vs time graphs on the HP Model 7275B plotter, or of saving the accumulated data to one of three floppy disc drives. If desired, the program also prints a table with the reading number, the percent strain and the time of the reading on the HP Think Jet printer.

E. TEMPERATURE CYCLING TESTS

The temperature cycling tests were similar to the creep tests with the exception that the temperature was raised 10°C above the initial test temperatures and after from four to eight hours, and was subsequently returned to the initial test temperature. This procedure was repeated until failure for each sample. The load and cycle times were such that each test would cycle several times over a two to four day period.

Later receipt of Eurotherm Model 808 programmable digital temperature controllers allowed precise control of temperature ramp, level, and dwell time. The PID features of these controllers also were adjusted to eliminate temperature over-shoot.

F. DATA REDUCTION

For the Instron tests, the raw data was obtained manually from the Instron strip chart recorder. The data from the plastic region were converted to true stress strain data by a program written in Basic for the NPS Mainframe computer (see Appendix G). The program was written to calculate a correction factor to account for mechanical slippage while testing. These data points were plotted using the Easyplot graphics routine on the NPS mainframe computer. The peak true stress from the above data was paired with the known applied strain rate to determine a single data point.

For the creep tests, the data was stored to 5 1/4 in floppy disc and output on the plotter. The creep rate in the secondary region was graphically determined from the true strain vs time creep curve and was paired with the known applied stress to constitute a single data point.

The temperature cycling test data was reduced in a similar manner as the creep tests. Additionally, the strain rate vs true strain graphs were plotted using a computer program written in HP Basic 2.0. This data reduction program was designed to be user-friendly and is menu-driven (see Appendix G). The menu choices included several types of graphs, true strain tables, strain rate tables, and calculation of activation energy. An example of the tables produced is in Appendix F.

The activation energies for the alloy were calculated from temperature cycling tests by graphical differentiation of the creep curve and were compared to the values of the activation energy for pure Al.

G. OPTICAL MICROSCOPY

Samples were mounted in Sample-Quik, manually ground to 600 grit, and polished with 3 μ m diamond paste. The samples were then electro-polished in Keller's reagent at 14 volts for 12 seconds, and anodized in Baker's solution at 14 volts for 60 seconds. The temperature of both processes was between -20 and -24°C. Optical micrographs were taken at various magnifications on a Zeiss optical microscope under plane polarized light.

IV. RESULTS AND DISCUSSION

A. MICROSCOPY

Optical microscopy was conducted by Ellison [Ref. 6] on as-rolled samples and on samples annealed at 500°C prior to creep testing. He reports that the as-rolled material exhibited grains somewhat elongated in the direction of rolling, consistent with the processes of fabrication. Subsequent annealing results in a microstructure that has large, equiaxed grains, which demonstrated that the anneal at 500°C for 15 minutes was sufficient to remove the effects of the rolling [Ref. 6]. Figure 6, presents a micrograph of the grip section from a sample deformed at 300°C.



Figure 6. Optical Micrograph of 300°C Sample:
Grip Section at 50x

It shows an equiaxed grain structure. Comparison with previous microscopy [Ref. 6] reveals the same microstructure and suggests little precipitation, either in grain interiors or upon grain boundaries, as a result of heating to 300°C.

B. CONSTANT EXTENSION RATE TESTS

Figure 7 summarizes typical results of Instron tests of the Al-2.0%Li alloy conducted at 300°C. Note that the material tested at the faster strain rate achieves a higher yield strength, rate of strain hardening and maximum stress than that at the slower rate. Under these conditions, strain hardening predominates the stress strain curve and there is no well-developed, steady-state behavior.

Figure 8 summarizes the results of Instron tests conducted at 450°C, and comparison to Figure 7 illustrates the effect of temperature. Note again that the material tested at the faster strain rate achieves a higher yield strength and maximum stress than that at the slower rate. However, under these conditions, softening of the material clearly predominates the stress strain curve. Deformation appears to occur at a nearly constant stress for strains above 10%, therefore, suggesting an approximate steady-state behavior of the alloy.

C. CONSTANT STRESS TESTS

In this portion of the research, specimens were tested at different stresses and secondary creep rates were calculated by graphical differentiation of the creep curves. Each specimen was tested to failure at a constant stress. Figure 9, in which true strain, ϵ , is plotted against time, shows a typical creep curve obtained at a temperature of 300 °C.

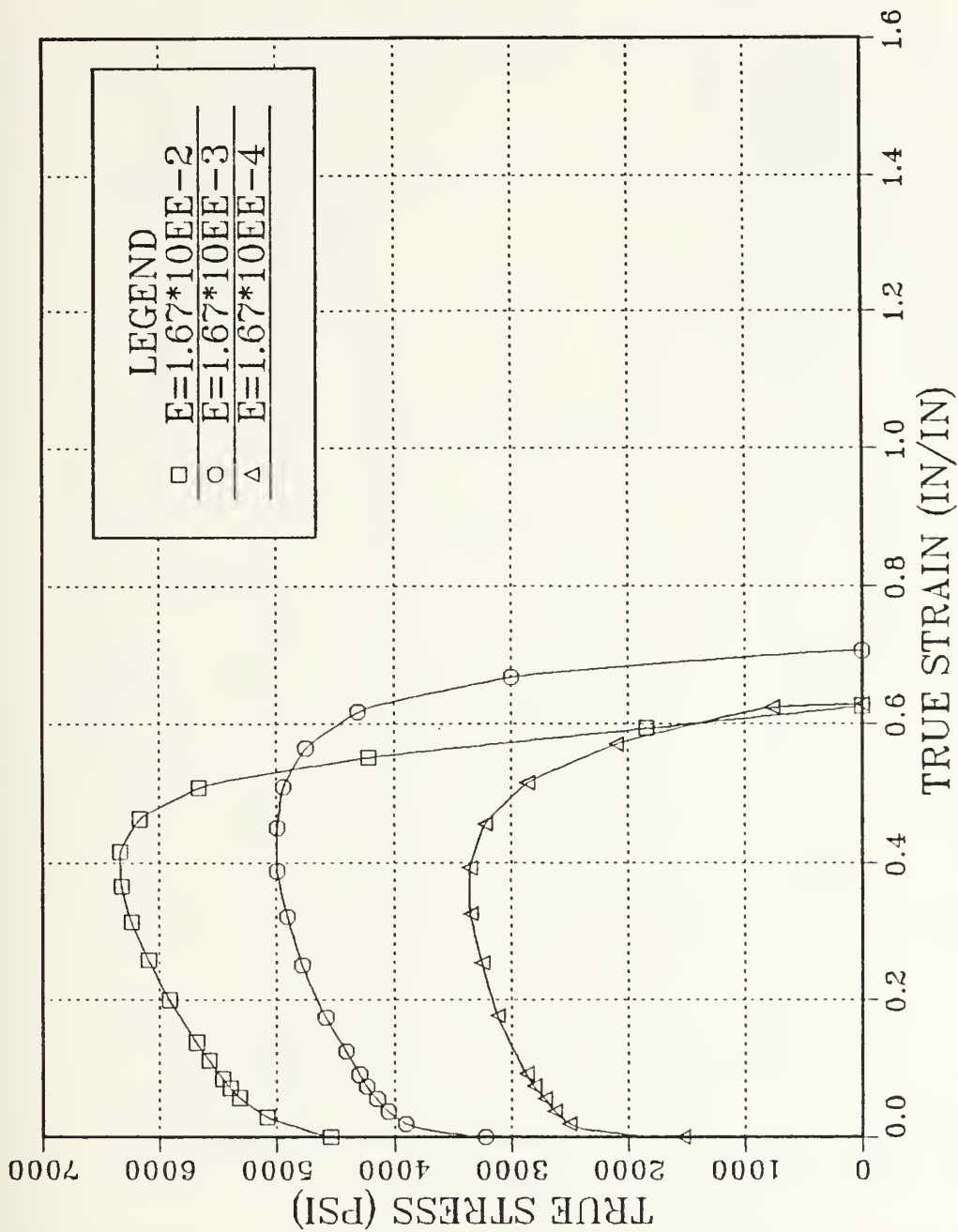


Figure 7. Stress Strain Curves at 300°C for Various Strain Rates

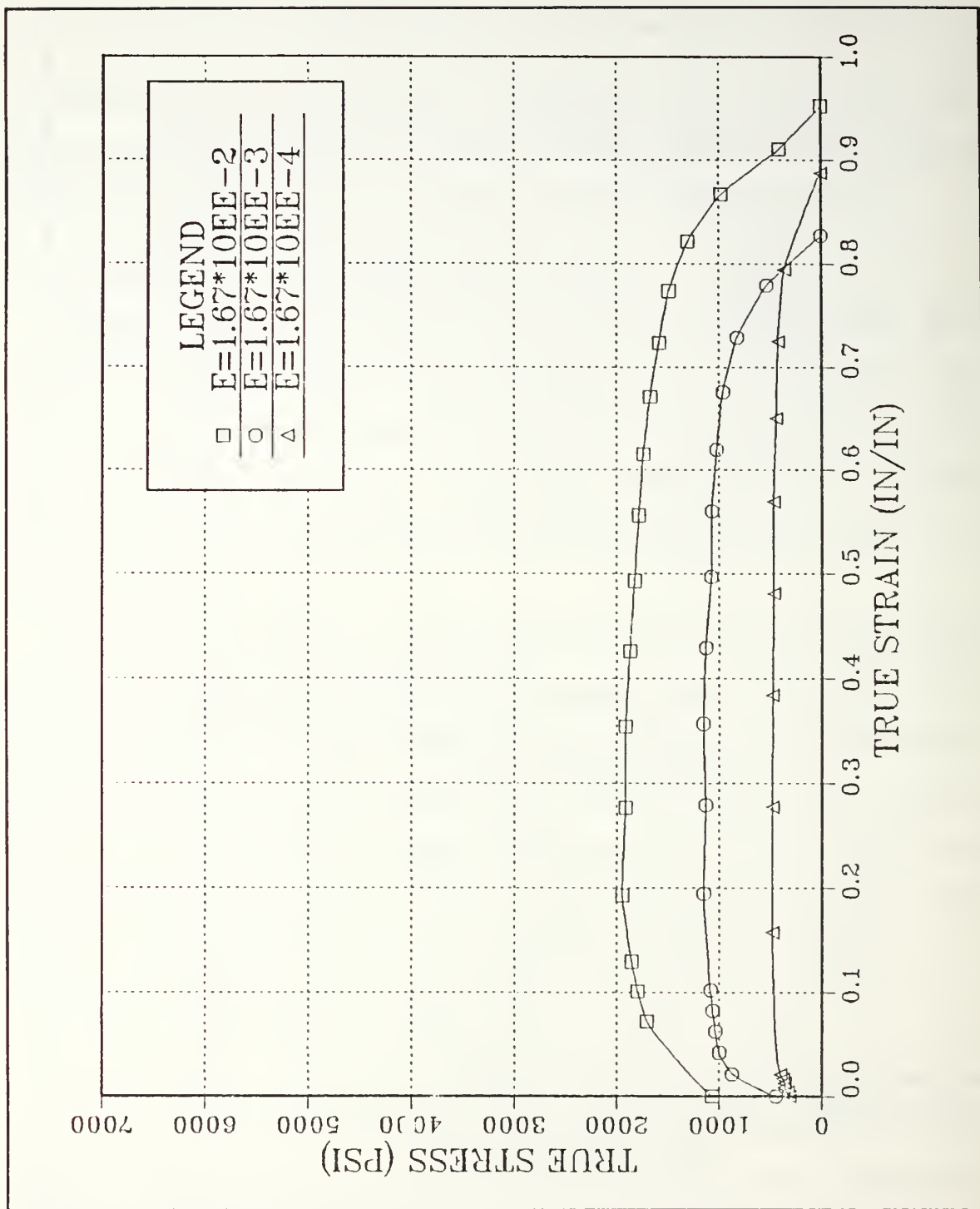


Figure 8. Stress Strain Curves at 450°C for Various Strain Rates

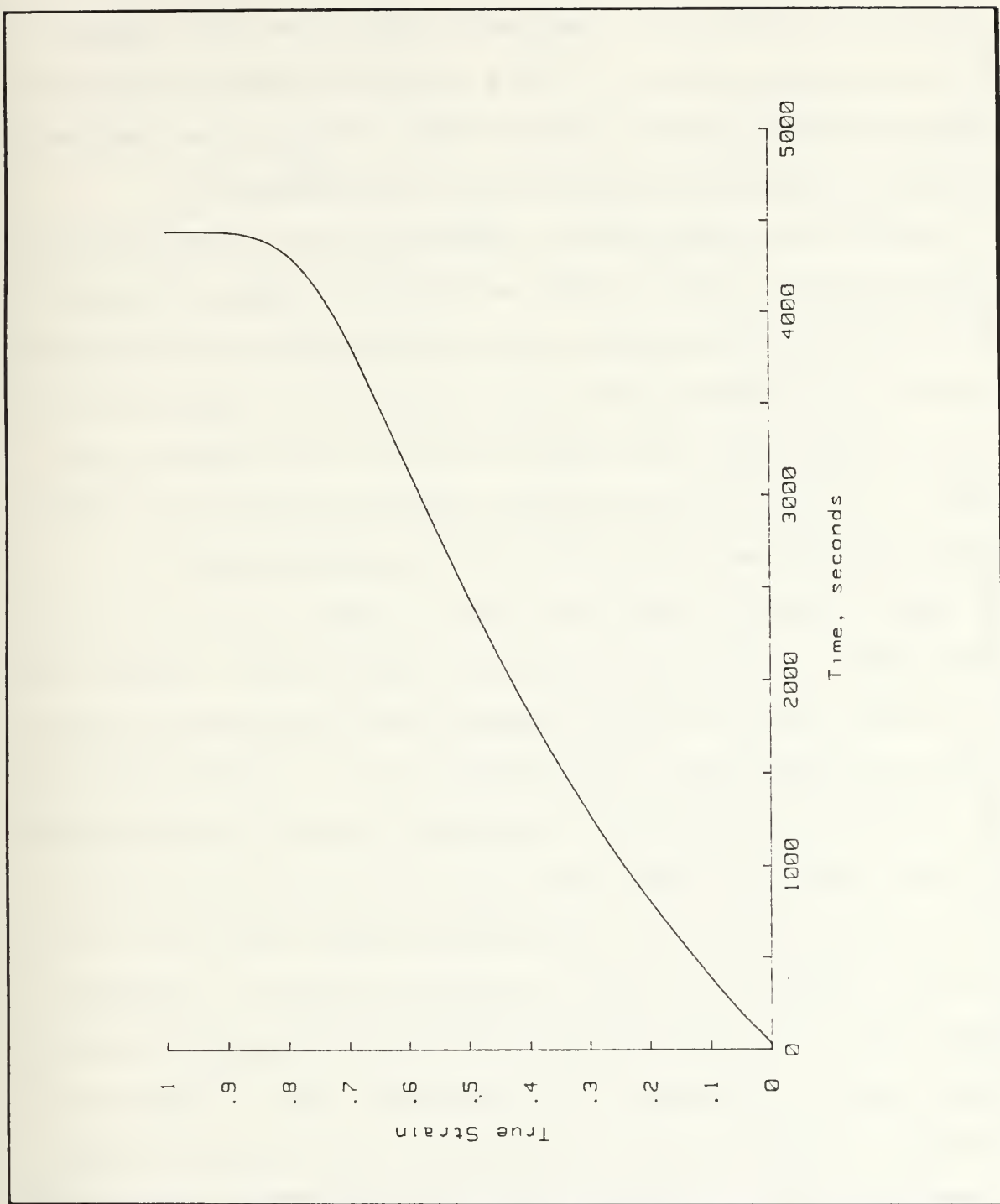


Figure 9. Creep Curve at 500°C for a Stress of 2.65 MPa:

$$\dot{\epsilon}_{\min} = 1.50 \times 10^{-4} \text{ sec}^{-1}$$

As seen in the figure, the creep curve exhibits three main features: a decelerating primary stage up to $\sim 50\%$, a well-defined secondary stage and an accelerating tertiary stage prior to sample failure. The shape of the creep curve is, therefore, similar to those reported for pure Al by Sherby.[Ref. 1]

The effect of the applied stress at a higher temperature is demonstrated by comparing Figure 9, tested at 500°C and 2.65 MPa, to Figure 10, tested at 500°C and 5.48 MPa (note that the creep results are represented on different time axes.). For a greater applied stress, the alloy sustains a higher creep rate. Also, the primary stage is less extensive at 500°C when compared to that at 300°C . For all tests in this investigation, creep rates increased as the applied load increased and creep rates increased as the temperature increased.

Figure 11 shows a typical creep rate, $\dot{\epsilon}$, versus true strain, ϵ , curve corresponding to the strain-time curve shown in Figure 9 above. The creep rate curve exhibits three main features: a distinct parabolic shape with the primary creep rate decreasing slowly, a clear inflection point at $\epsilon \sim 0.58$ where the creep rate goes through a minimum and a pronounced increase in the tertiary creep rate prior to failure. The shape of the creep rate curve is, therefore, similar to those reported by Smith [Ref. 9]. The jagged appearance of the curve is due to the effects of quantization errors in the acquisition equipment. The analog-to-digital (a/d) converter must represent a continuous-time signal in a discrete manner and may not distinguish close, yet different, values of voltages sent it from the LVDT and its amplifier. The threshold of each level must be enough to cause the a/d converter to ascend to the next discrete level. Additional errors are introduced since the voltage values are truncated when each value is converted to binary code for mass storage on the floppy disc.

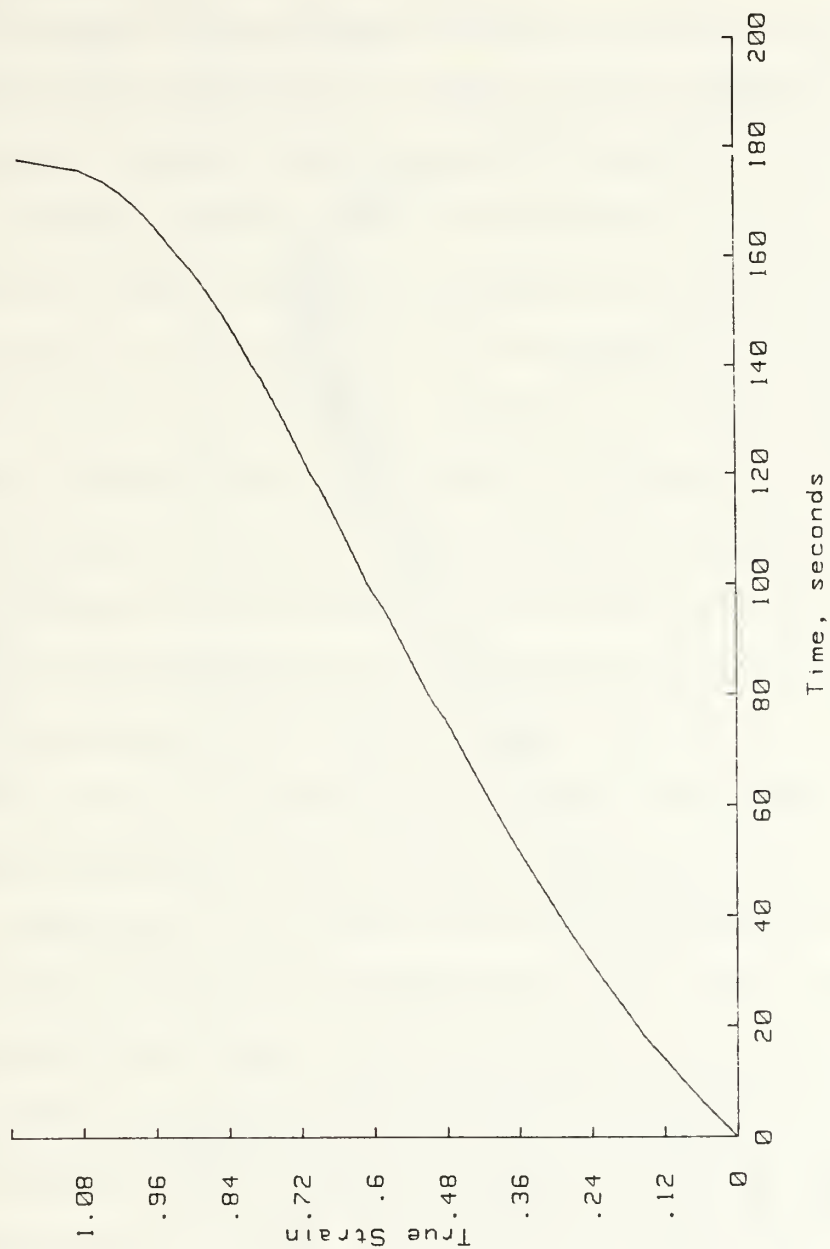


Figure 10. Creep Curve at 500°C for a Stress of 5.48 MPa:

$$\dot{\epsilon}_{\min} = 4.83 \times 10^{-3} \text{ sec}^{-1}$$

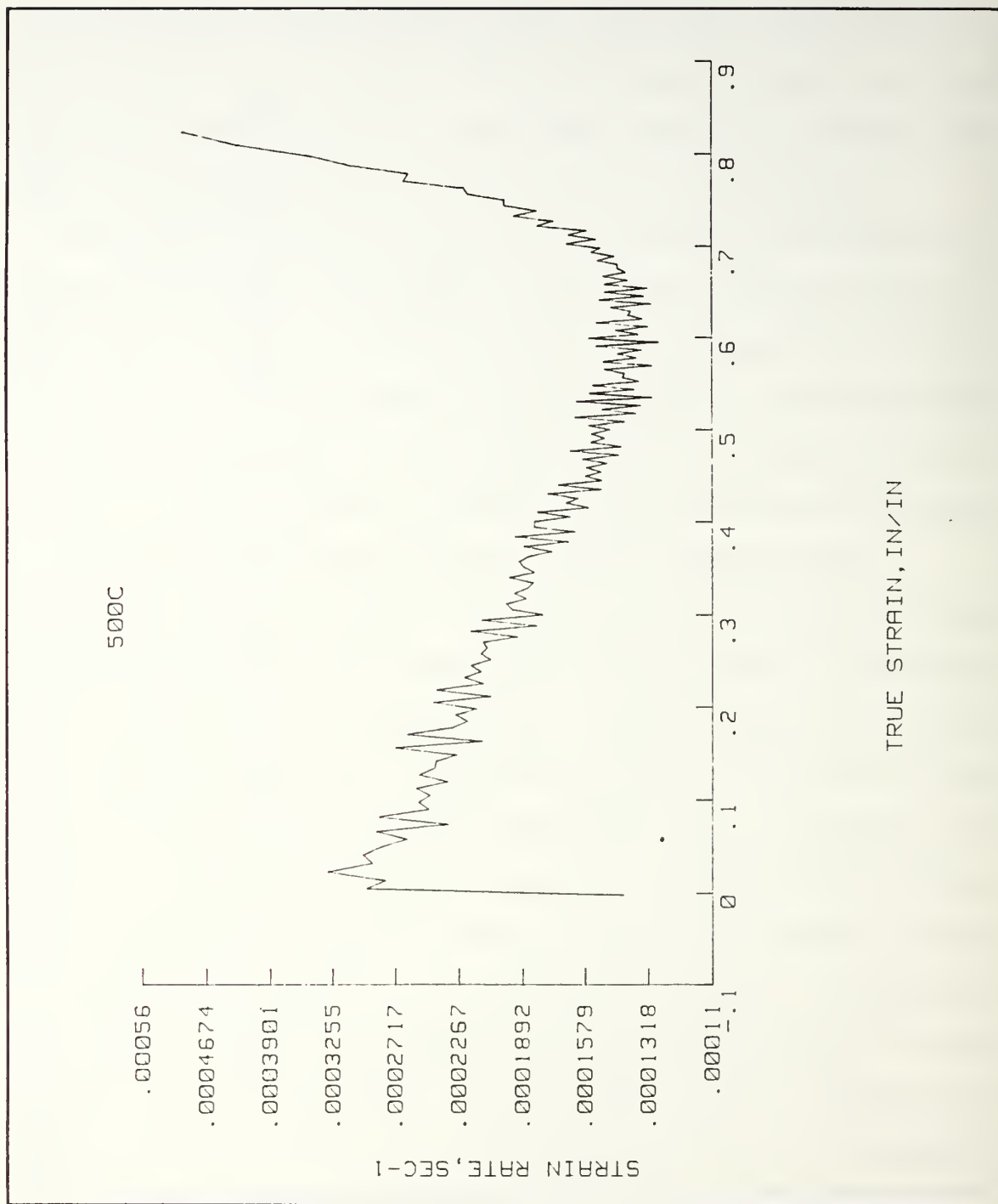


Figure 11. Creep Rate Curve at 500°C for a Stress of 2.65 MPa:

$$\dot{\epsilon}_{\min} = 1.43 \times 10^{-4} \text{ sec}^{-1}$$

D. TEMPERATURE CYCLING TESTS

In this procedure, several identical specimens were crept at a constant stress, σ , while the initial temperature, T_1 , is rapidly increased. Within 10 minutes of the temperature increase, sufficient strain had accumulated to ascertain the presence of the new creep rate. This new temperature level, T_2 , was held for several hours. Finally, the increased temperature is rapidly decreased to its original value of T_1 and the cycling of the temperature in this manner is continued through steady-state and up until failure. A typical example for the application of this procedure at 350°C is shown in Figure 12, in which the true strain, ϵ , is plotted as a function of time. Examination of these data reveals that there is a similarity between temperature cycling creep curves and isothermal creep curves and that the duration of the temperature excursion from T_1 to T_2 is nominal when compared to the overall duration of the test.

Figure 13 reveals a typical creep rate versus creep strain curve for the temperature cycling tests in which creep rate, $\dot{\epsilon}$, is plotted as a function of creep strain, ϵ . Examination of the figure reveals three important points. First, the creep rate, after the temperature increase from 350 to 360°C, increases and quickly reaches the new value. Second, in the minimum creep rate region, the creep rate after the temperature change from 350 to 360°C reaches a value that essentially agrees with the original steady-state rate established before the temperature increase to 360°C. Third, the creep transient after a temperature change, is identical to that of pure Al, as reported previously by Lytton *et al.*[Ref. 10]

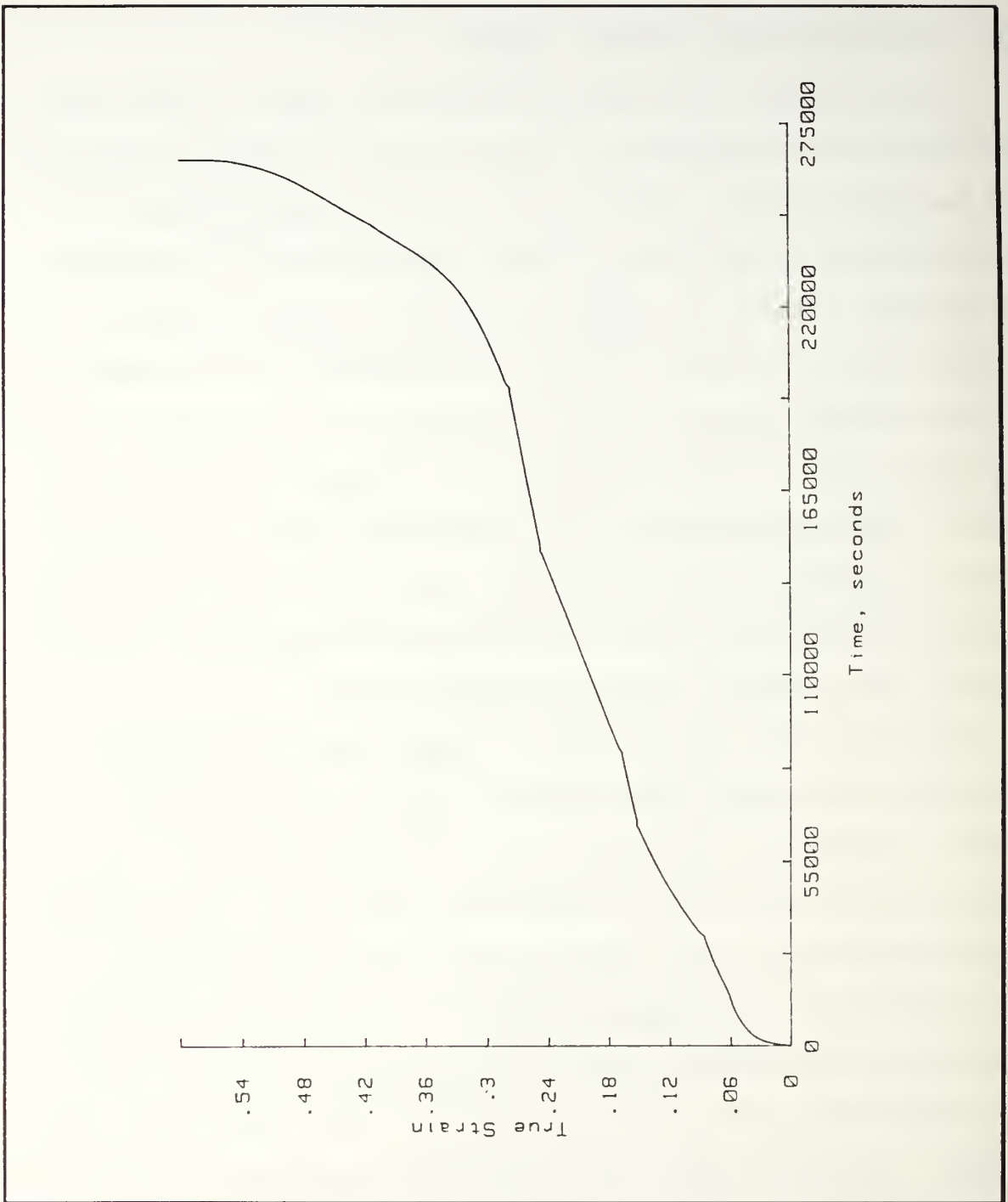


Figure 12. Creep Curve at 350-360°C for a Stress of 6.38 MPa:

$$\dot{\epsilon}_1 = 1.28 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 6.55 \times 10^{-7} \text{ sec}^{-1}$$

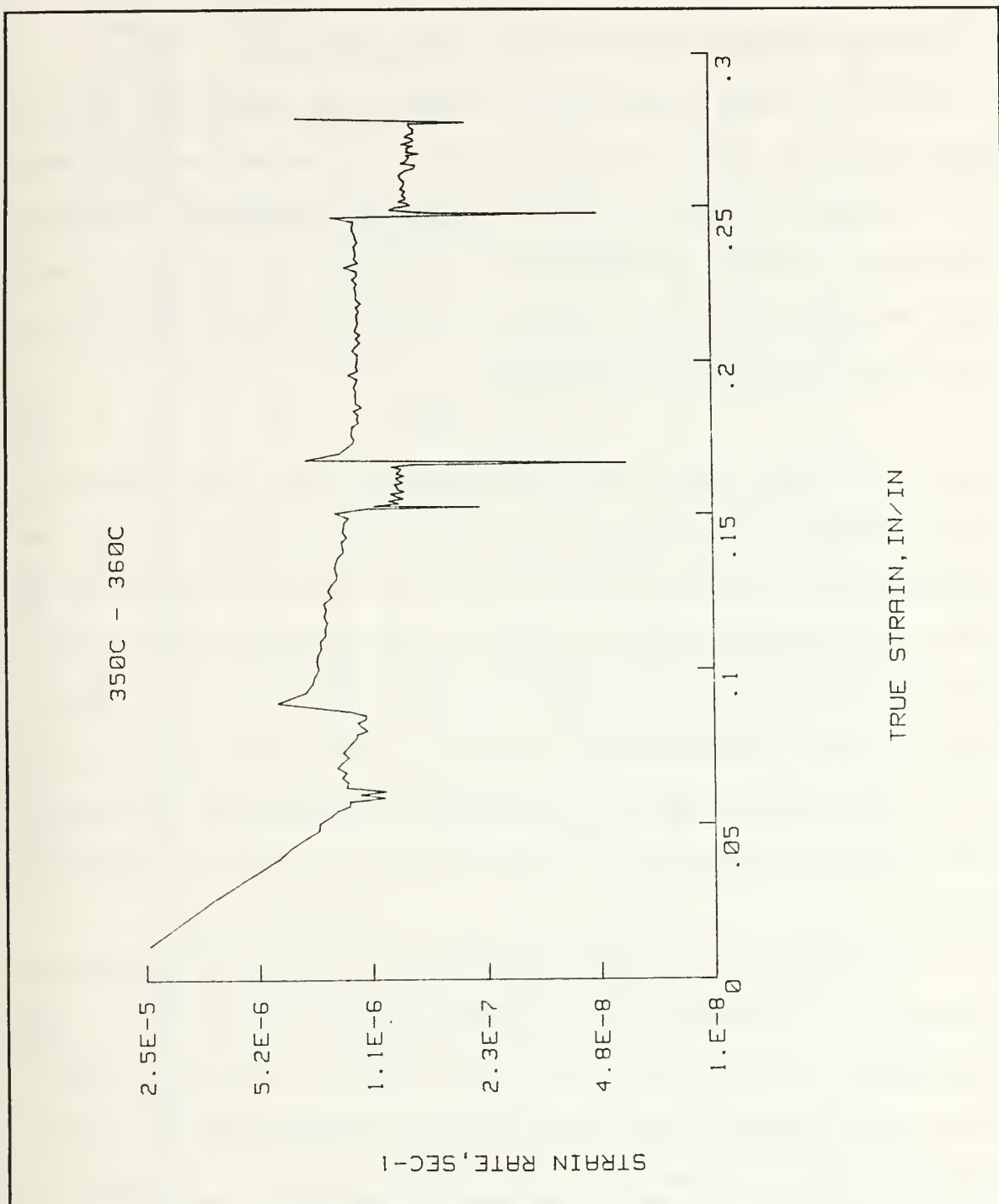


Figure 13. Creep Rate Curve at 350-360°C for a Stress of 6.38 MPa: $\dot{\epsilon}_1 = 1.28 \times 10^{-6} \text{ sec}^{-1}$ & $\dot{\epsilon}_2 = 6.55 \times 10^{-7} \text{ sec}^{-1}$

E. STRESS DEPENDENCE OF THE STRAIN RATE

The data of Table 2 summarize the results of the uninterrupted tests to failure and may be utilized to determine the stress and temperature dependence of the strain rate and thus facilitate determination of the underlying mechanisms of deformation. Sherby and Burke [Ref. 1] note that, for an intermediate stress range, the relationship between strain rate and stress at constant temperature can be described by the power-law relationship:

$$\dot{\epsilon}_{\min} = K\sigma^n \quad (4)$$

values of n for pure metals (Al) are usually equal to 5. The experimental values of $\log \dot{\epsilon}$ obtained in this research were plotted versus $\log \sigma$ for each test temperature. The results are shown in Figure 14. The stress exponent for Al-2.0%Li, as calculated from the slopes of the isothermal curves, shows dependence on temperature such that n is 6.7 at 300°C and 6.0 at 350°C. However, at 400, 450 and 500°C, n is relatively constant with values of 5.0, 4.8 and 4.9, respectively, and appears to be independent of temperature in this range. These n values, calculated from the data by linear regression, are compiled in Table 3.

For comparison purposes, data from Park *et al* [Ref. 11], who conducted creep tests of Al-2.1wt%Li in the temperature range of 500 to 560°C and utilizing double shear specimens, are plotted on Figure 14. Note that at 500°C the two data sets differ by a factor of 2 which is considered excellent agreement given the different test methods. The stress exponent for Al-2.1%Li, as estimated from the slope of the plot, is essentially independent of temperature and is close to a value of 4.6. The stress exponent from this investigation at

Table 2. SUMMARY OF Al-2.0%Li RESULTS

Type	#	Temp (°C)	$\dot{\epsilon}$ (sec ⁻¹)	σ (MPa)	log $\dot{\epsilon}$	log σ	$\dot{\epsilon} / D$ (m ⁻²)	σ / E	% Elongation
Instron	1	300	1.67 x 10 ⁻²	43.7	-1.78	1.64	1.01 x 10 ¹⁵	7.24 x 10 ⁻⁴	87.6
Instron	16	300	1.67 x 10 ⁻³	34.4	-2.78	1.54	1.01 x 10 ¹⁴	5.71 x 10 ⁻⁴	110
Instron	27	300	1.67 x 10 ⁻⁴	23.1	-3.78	1.37	1.01 x 10 ¹³	3.83 x 10 ⁻⁴	91.0
Creep	3	300	6.40 x 10 ⁻⁵	21.2	-4.19	1.33	3.87 x 10 ¹²	3.52 x 10 ⁻⁴	152
Creep	4	300	3.25 x 10 ⁻⁵	19.0	-4.49	1.28	1.97 x 10 ¹²	3.15 x 10 ⁻⁴	144
Creep	5	300	4.24 x 10 ⁻⁶	13.0	-5.38	1.11	2.54 x 10 ¹¹	2.15 x 10 ⁻⁴	119
Instron	19	350	1.67 x 10 ⁻²	31.1	-1.78	1.49	9.12 x 10 ¹³	5.43 x 10 ⁻⁴	80.0
Creep	11	350	1.90 x 10 ⁻³	21.2	-2.72	1.33	1.04 x 10 ¹³	3.70 x 10 ⁻⁴	141
Instron	17	350	1.67 x 10 ⁻³	21.4	-2.78	1.33	9.12 x 10 ¹²	3.73 x 10 ⁻⁴	103
Instron	25	350	1.67 x 10 ⁻⁴	13.6	-3.78	1.13	9.12 x 10 ¹¹	2.37 x 10 ⁻⁴	95.0
Creep	13	350	8.88 x 10 ⁻⁵	12.9	-4.05	1.11	4.85 x 10 ¹¹	2.24 x 10 ⁻⁴	155
Creep	26	350	1.93 x 10 ⁻⁶	7.00	-5.71	0.85	1.05 x 10 ¹⁰	1.22 x 10 ⁻⁴	88.0

Table 2. (Continued)

Type	#	Temp (°C)	$\dot{\epsilon}$ (sec ⁻¹)	σ (MPa)	log $\dot{\epsilon}$	log σ	$\dot{\epsilon} / D$ (m ⁻²)	σ / E	% Elongation
Instron	21	400	1.67×10^{-2}	22.2	-1.78	1.35	1.18×10^{13}	4.05×10^{-4}	103
Instron	20	400	1.67×10^{-3}	14.4	-2.78	1.15	1.18×10^{12}	2.56×10^{-4}	99.0
Instron	22	400	1.67×10^{-4}	8.71	-3.78	0.94	1.18×10^{11}	1.59×10^{-4}	93.0
Creep	23	400	9.00×10^{-5}	7.10	-4.05	0.85	6.34×10^{10}	1.29×10^{-4}	167
Creep	24	400	1.71×10^{-5}	5.24	-4.49	0.72	1.20×10^{10}	9.54×10^{-5}	103
Creep	18	400	1.83×10^{-6}	3.76	-5.74	0.57	1.29×10^9	6.84×10^{-5}	88.0
Instron	38	450	1.67×10^{-2}	13.4	-1.78	1.13	2.02×10^{12}	2.58×10^{-4}	157
Instron	32	450	1.67×10^{-3}	7.96	-2.78	0.90	2.02×10^{11}	1.53×10^{-4}	134
Instron	53	450	1.67×10^{-4}	--	-3.78	--	2.02×10^{10}	-- $\times 10^{-4}$	143
Creep	35	450	4.43×10^{-5}	3.90	-4.35	0.59	5.35×10^9	7.50×10^{-5}	133
Creep	34	450	5.15×10^{-6}	2.46	-5.29	0.39	6.22×10^8	4.73×10^{-5}	80.0
Instron	45	500	1.67×10^{-2}	8.08	-1.78	0.91	4.34×10^{11}	1.61×10^{-4}	112

Table 2. (Continued)

Type	#	Temp (°C)	$\dot{\epsilon}$ (sec ⁻¹)	σ (MPa)	log $\dot{\epsilon}$	log σ	$\dot{\epsilon} / D$ (m ⁻²)	σ / E	% Elongation
Creep	41	500	4.83×10^{-3}	5.48	-2.32	0.74	1.26×10^{11}	1.10×10^{-4}	194
Instron	51	500	1.67×10^{-3}	4.27	-2.78	0.63	4.34×10^{10}	8.54×10^{-5}	123
Creep	40	500	2.43×10^{-4}	3.67	-3.61	0.57	6.31×10^9	7.34×10^{-5}	119
Instron	52	500	1.67×10^{-4}	3.02	-3.78	0.48	4.34×10^9	6.04×10^{-5}	95.0
Creep	39	500	1.50×10^{-4}	2.65	-3.84	0.42	3.90×10^9	5.30×10^{-5}	131
Creep	46	500	1.49×10^{-4}	2.65	-3.83	0.42	3.87×10^9	5.30×10^{-5}	(arrested)
Creep	37	500	6.59×10^{-5}	2.25	-4.20	0.35	1.71×10^9	4.50×10^{-5}	67.0
Creep	44	500	1.20×10^{-5}	1.84	-4.92	0.27	3.12×10^8	3.68×10^{-5}	60.0
Creep	55	500	6.00×10^{-6}	1.63	-5.22	0.21	1.56×10^8	3.26×10^{-5}	56.0

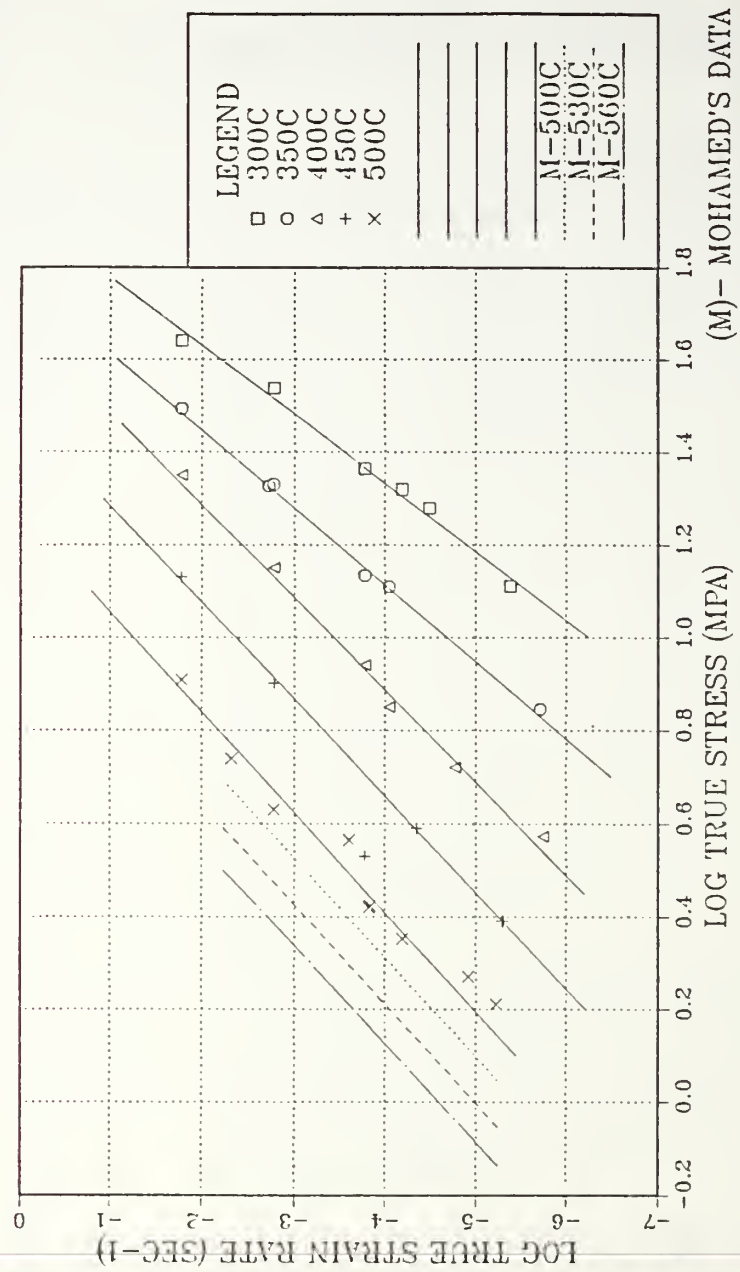


Figure 14. Log-Log Curves of Strain Rate Vs. True Stress

Table 3. STRESS EXPONENT

Temp (°C)	Value of n
300	6.7
350	6.0
400	5.0
450	4.8
500	4.9

500°C is 4.9 and also compares well with the value reported in the work of Park *et al.*[Ref. 11].

From the n values obtained in this investigation, it is surmised that the mechanisms of creep in the temperature range of 400 to 500°C are similar to that of pure Al, which deforms by glide and climb of dislocations, with diffusion-controlled climb determining the overall rate of straining.

F. MICROSTRUCTURAL EVOLUTION DURING CREEP

Optical microscopy was conducted on fractured samples from the 300°C and the 500°C creep tests. Figure 15(a), a photo-micrograph of the gauge section of a coupon tested at 300°C, was taken at a low magnification of 50x. It illustrates the elongated grains due to creep in the direction of straining. Sub-structures have formed within the grains, as evidenced by the mottled contrast. This is in accordance with class II deformation behavior, and can be distinguished more readily in Figure 15(b), a micrograph of the same region, but at a magnification of 200x. The sub grains are well delineated in the grain to the right of center of

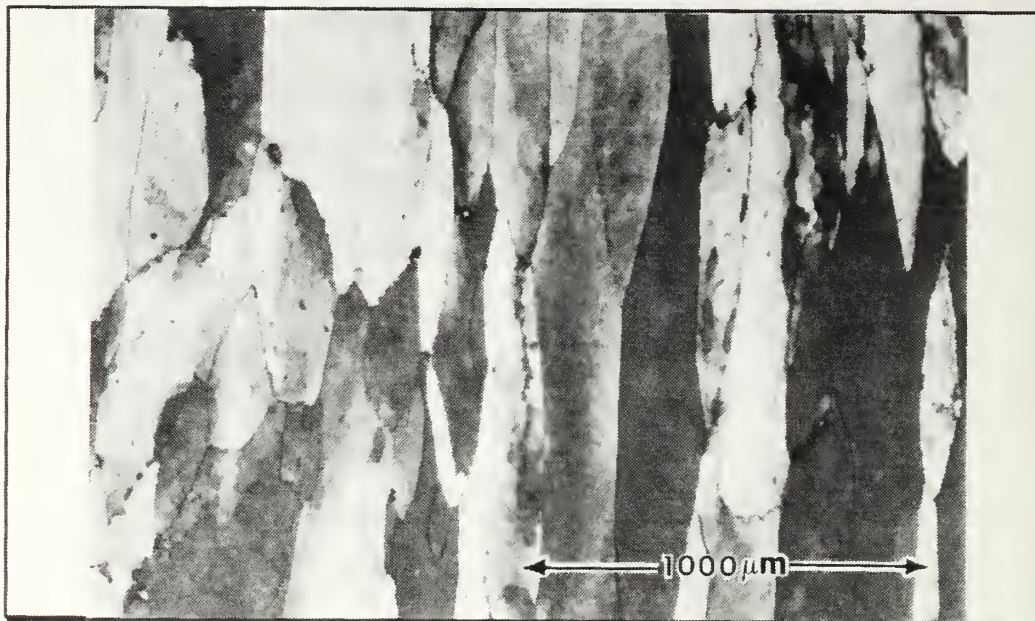


Figure 15(a). Optical Micrograph of 300°C Sample:
Gauge Section at 50x

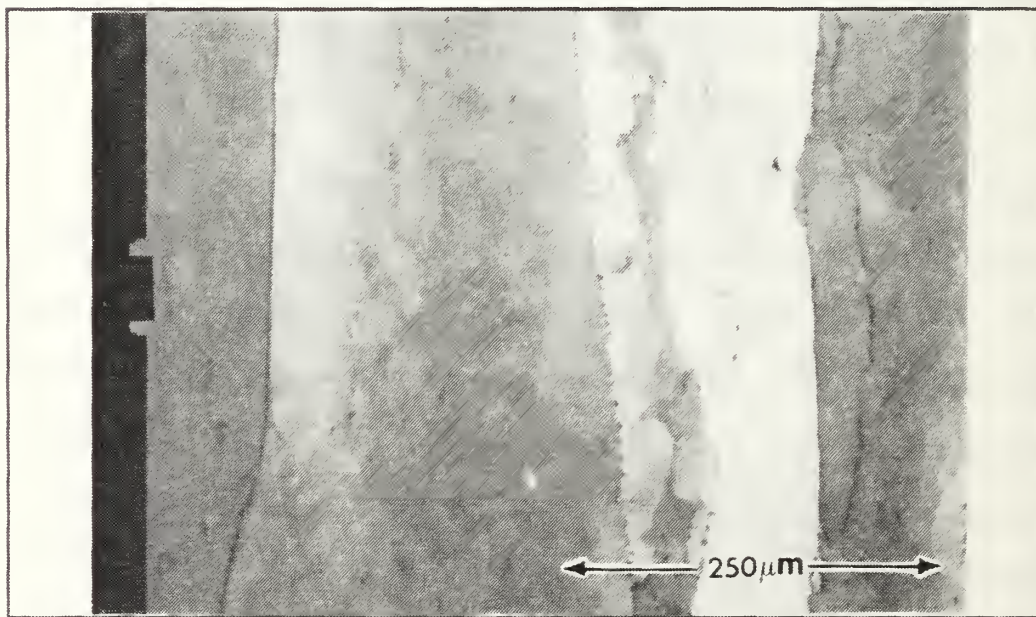


Figure 15(b). Optical Micrograph of 300°C Sample:
Gauge Section at 200x

the field of view. Intergranular precipitation is also evident and likely consists of δ' phase on the prior boundaries of the solid solution.

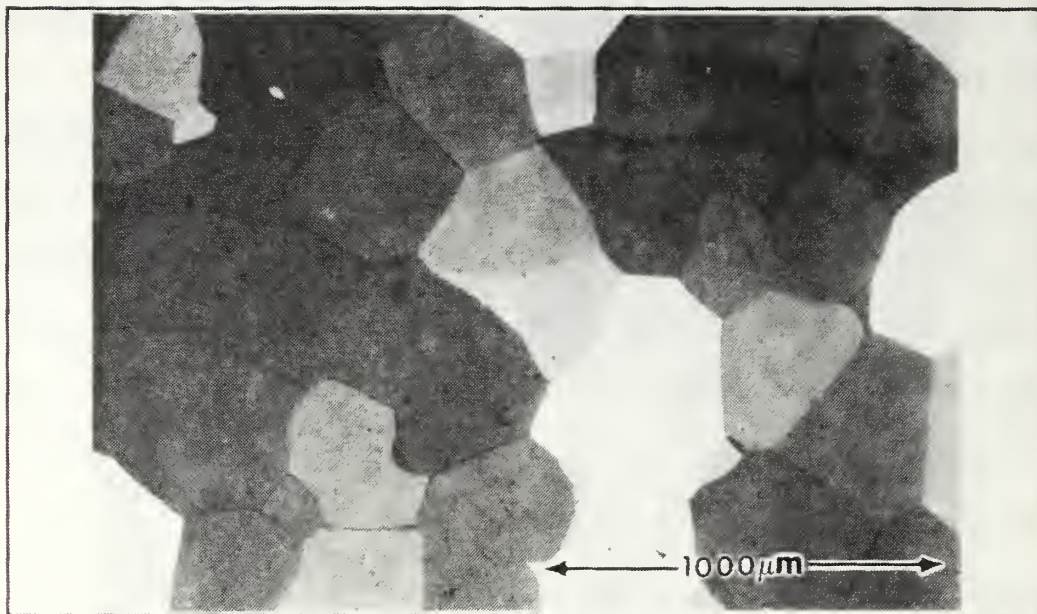
Figure 16 shows a micrograph of the grip section of a sample crept at 500°C and was obtained at 50x. Larger grains due to grain growth at the higher temperature are evident. Figure 17 is a micrograph of this 500°C sample's gauge section, also at a magnification of 50x. Grain growth due to temperature and strain is evident. A coarser subgrain structure (when compared to the sample deformed at 300°C) is also evident in this micrograph and appears as irregular grain boundaries.

G. ACTIVATION ENERGY FOR CREEP

The data of Table 4 summarize the results of the temperature cycling tests and may be utilized to determine the stress and temperature dependence of the activation energy for creep, Q_C . Assuming creep is thermally activated and follows an Arrhenius temperature dependence at constant stress, a value for Q_C can be obtained from equation 8. Determination of Q_C was accomplished by the previously described technique of evaluating the steady-state creep rate preceeding and following a small, abrupt change in temperature. Temperature differences of 10°C were used. The creep rates were determined by graphical differentiation of the strain versus time curves. All activation energies reported in this paper were plotted in terms of the mean test temperature [Ref. 10] defined as:

$$\frac{1}{T} = \frac{1}{2} \left(\frac{1}{T_1} + \frac{1}{T_2} \right) \quad (12).$$

The results are summarized graphically in Figure 18. Values of Q_C at 300 and 350°C are 47.4 and 52.3 kcal/mole, respectively. The activation energy, Q_C ,



**Figure 16. Optical Micrograph of 500°C Sample:
Grip Section at 50x**



**Figure 17. Optical Micrograph of 500°C Sample:
Gauge Section at 50x**

Table 4. SUMMARY OF Al-2.0%Li TEMPERATURE CYCLING RESULTS

#	Temp (°C)	Mean Temp (°C)	$\dot{\epsilon}_L$ (sec ⁻¹)	$\dot{\epsilon}_H$ (sec ⁻¹)	Q_C (kcal/mole)
48	300-310	305	2.10×10^{-6}	4.30×10^{-6}	47.4
28	350-360	355	1.28×10^{-6}	6.55×10^{-7}	52.3
29	400-410	405	1.18×10^{-6}	2.22×10^{-6}	57.5
30	400-410	405	3.98×10^{-7}	7.31×10^{-7}	55.3
34	450-460	455	5.51×10^{-6}	8.69×10^{-6}	54.9
54	470-480	475	1.75×10^{-6}	2.52×10^{-6}	40.4
36	500-510	505	1.51×10^{-6}	1.99×10^{-6}	33.1

reaches its maximum value of 56.4 kcal/mole at 400°C and then drops rapidly at 470 and 500°C to values of 40.2 and 33.1 kcal/mole, respectively. Note that Q_C for pure Al in the temperature range 300 to 500°C (573 to 773K) is constant at approximately 35.5 kcal/mole [Ref. 10].

Therefore, although the Al-2.0%Li alloy exhibits a similar stress dependence and formation of subgrain structures as observed in pure Al, the values of Q_C are appreciably higher. Table 5 is a compilation of activation energy results for this alloy. The data were obtained by three different computational methods. The first method used graphical differentiation directly applied to the individual creep curves. The second method involved use of linear regression applied to the creep rate versus creep strain curves. The third method calculated Q_C from the difference between the isothermal $\log \dot{\epsilon}$ vs. $\log \sigma$ plots for data obtained at constant stress. All methods involved similar values of strain rate which were then employed with equation 8 for determination of Q_C . The values from the

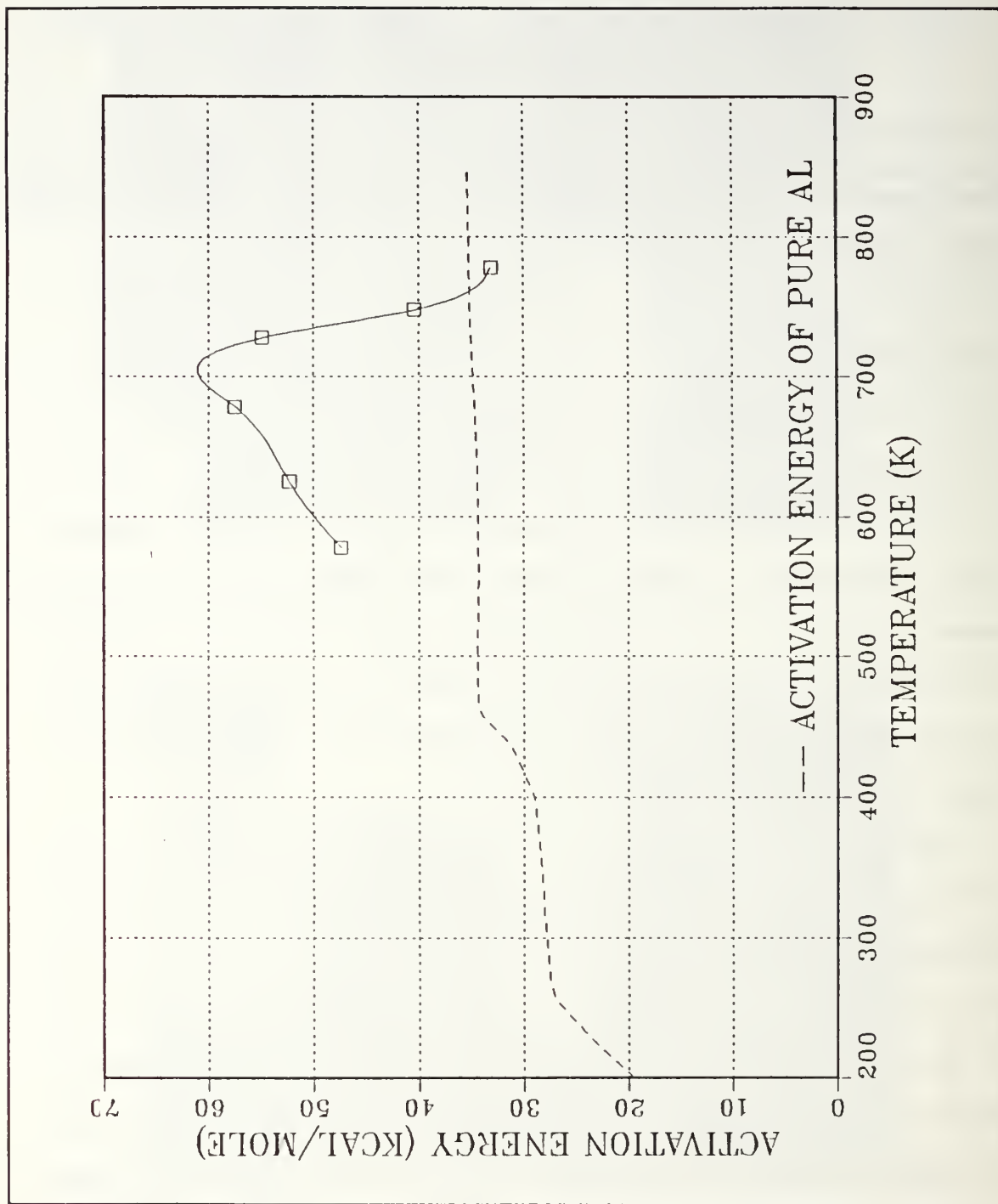


Figure 18. Al-2.0%Li Activation Energy Curve Compared to Pure Al

direct analysis of the creep curves and from the creep rate curves (i.e. from the differentiated creep curves) yield close agreement, as expected. Figure 19 gives further insight into the behavior of the activation energy for the Al-Li system. This figure graphically compares Q_c for Al with 0.5, 1.0, and 2.0wt% Li additions. The data for the 0.5 and 1.0% Li additions are taken from the NPS study by Taylor [Ref. 5]. As Li content increases, the observed activation energy becomes progressively higher within the temperature interval 600 to 725K. The peak activation energy values are in order of Li addition: Q_c for Al-2.0%Li peaks at 56.4 kcal/mole at 700K; Q_c for Al-1.0%Li peaks at 54 kcal/mole and ~700K; and Q_c for Al-0.5%Li peaks at 51 kcal/mole at 700K to 750K.

Table 5. SUMMARY OF Al-2.0%Li ACTIVATION ENERGY RESULTS IN KCAL/MOLE

#	Temp (°C)	Mean Temp (°C)	Creep Curves	Creep Rate	Log-Log Curve
48	300-310	304.92	47.4	45.9	42.5
28	350-360	354.93	52.3	50.9	55.9
29	400-410	404.94	57.5	55.6	49.0
30	400-410	404.94	55.3	62.7	49.0
34	450-460	454.95	54.9	54.6	54.4
54	470-480	474.95	40.4	*	--
36	500-510	504.95	33.1	*	--
* Note: these values were not obtained due to limits in the data acquisition system					

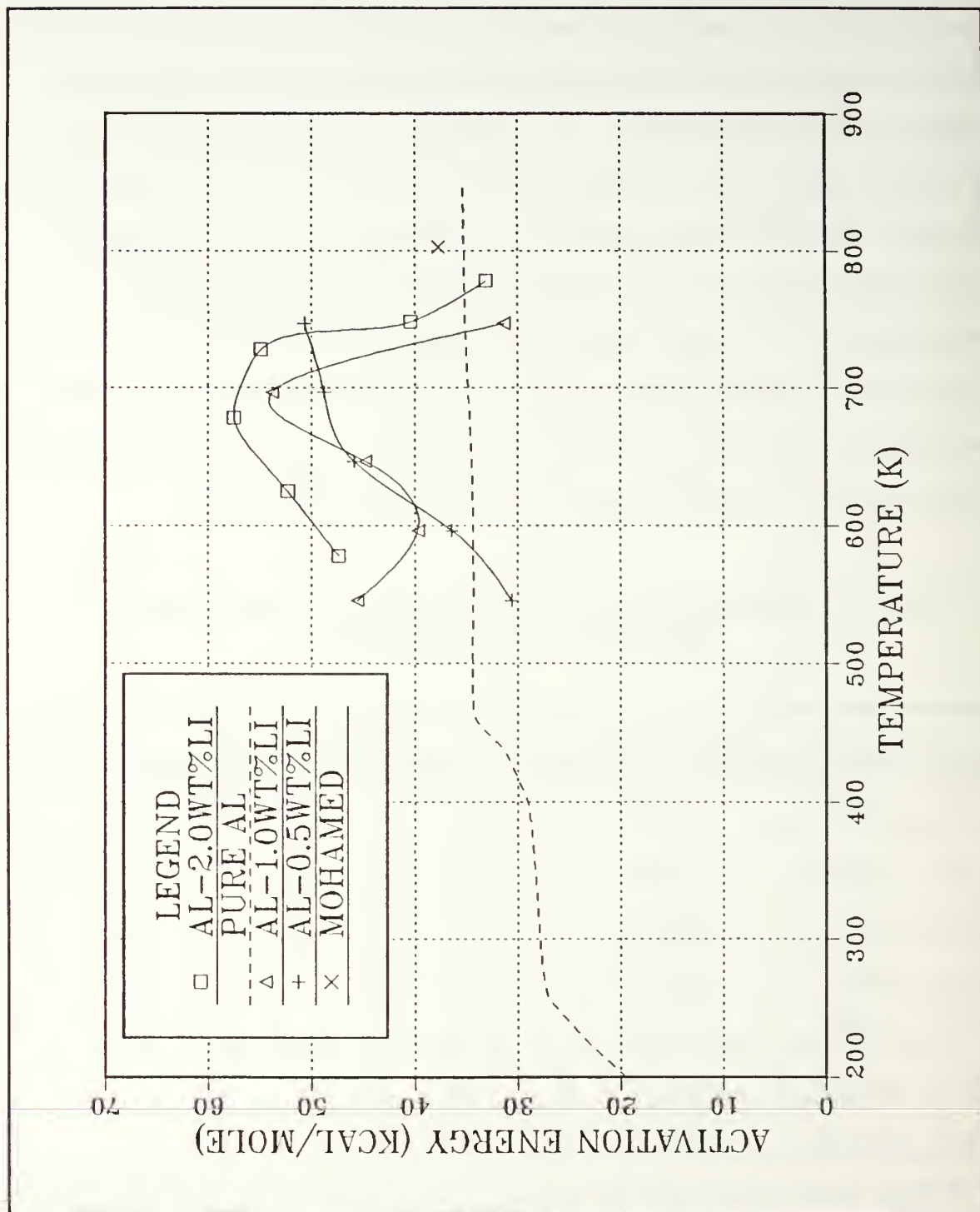


Figure 19. Activation Energy Versus Temperature for Al with 0.5, 1.0, and 2.0% Li Additions

H. NORMALIZED RESULTS

Further insight into the behavior of the Al-2.0%Li can be obtained by replotting the data as $\dot{\epsilon}/D$ vs. σ/E on double logarithmic axes, as shown in Figure 20. Diffusion and modulus data were those for Al because data for Al-2.0%Li was unavailable. The data appears similar to the Al data as modelled by the Wu-Sherby relationship [Ref. 12]:

$$\dot{\epsilon}_{\min} = \frac{K D_{\text{eff}}}{\alpha^n b^2} \left(\sinh \alpha \frac{\sigma}{E} \right)^n \quad (11)$$

where $K = 2 \times 10^{12}$, b = Burger's vector ($2.8 \times 10^{-10}\text{m}$), $\alpha = 2600$ and $n = 5$. The effective diffusion coefficient, D_{eff} , is essentially the lattice diffusion coefficient, D_l , modified to account for the enhancement of diffusion resulting from pipe diffusion. The stress dependence of the data is in close agreement with that of equation 11. However two observations can be made: as temperature decreases, the degree of alloy strengthening relative to Al increases; and, as the strain rate at a specific temperature decreases, the degree of alloy strengthening increases. This suggests that the temperature dependence of the normalizing values for the alloy is different from the temperature dependence of those values for the pure metal.

Stacking fault energy and modulus are a function of temperature. If these functions for the alloy are the same as for the pure metal, then one would expect little or no variation in the normalized data for the two cases. However, as noted earlier, the activation energy for the alloy from 300 to 450°C is appreciably greater than for the pure metal. This may be an indication that the temperature dependence of stacking fault energy and modulus is also different for the alloy, leading to the apparent scatter of data in the normalized presentation.

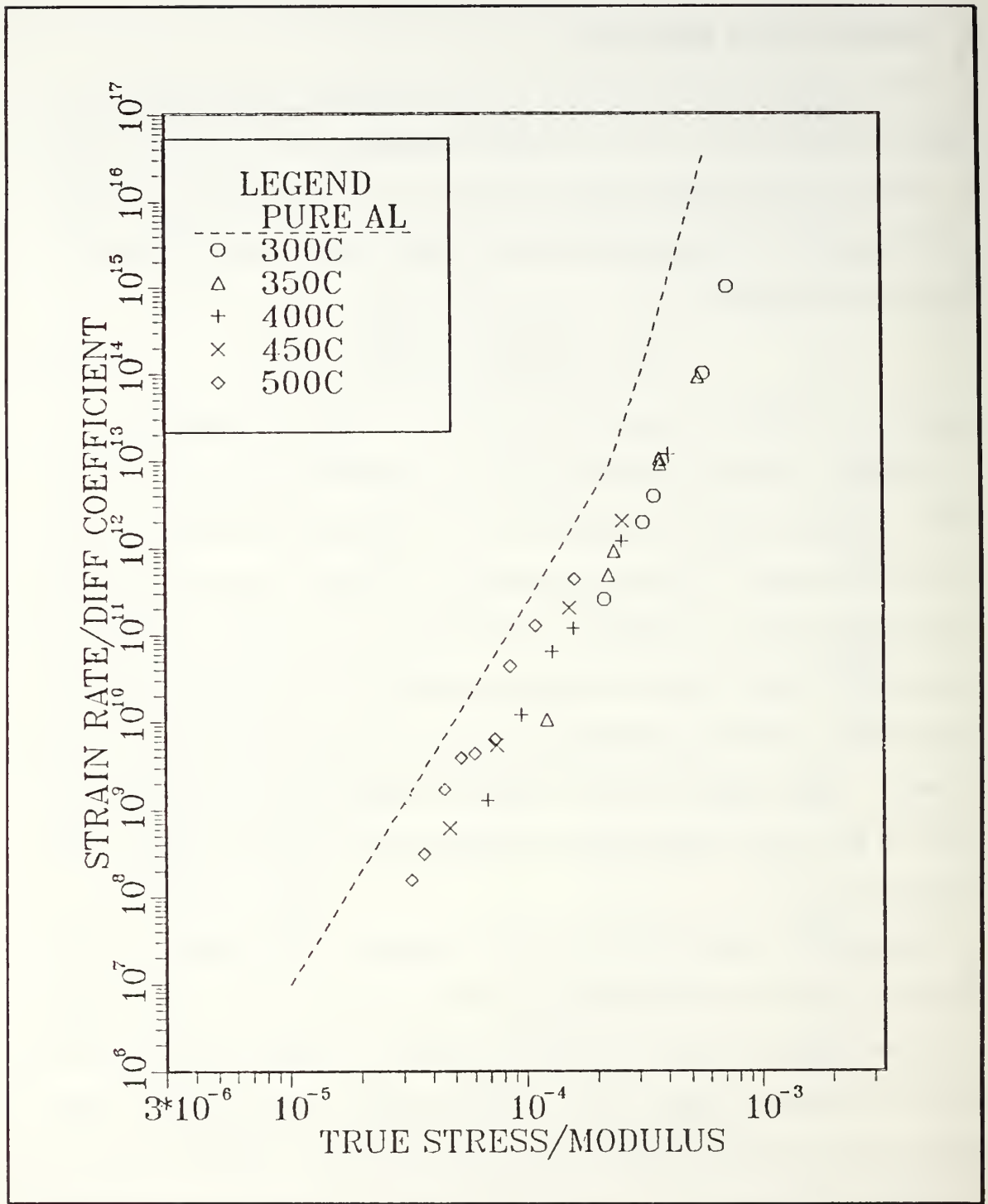


Figure 20. Al-2.0%Li $\dot{\epsilon} / D$ vs. σ / E as Compared to Pure Al

I. INTERPRETATION OF RESULTS

First, the stress dependence of creep for the alloy is the same as that for pure Al. Second, the observation of sub-grain formation following the extensive primary stages of creep is also identical to the creep mechanisms of the pure metal. Third, the activation energy clearly exhibits a notably different temperature dependence than does the activation energy for pure Al. The activation energy may be considered a summation of self-diffusion, stacking fault energy and modulus components (equation 10). As noted earlier in Chapter II, the addition of Li to Al has the effect of increasing the modulus due to the effect of Li on bonding in the ordered structure. If the alloy were to undergo an order/disorder transition, e.g. in the temperature range between 400°C and 500°C, this could result in a more rapid decrease in modulus than for the pure metal and could account for the values of Q_c being greater than those for self-diffusion in this temperature regime.

While the creep characteristics of Al-2.0%Li resemble those of Al, there is strengthening due to the Li addition and the magnitude of the strengthening increases as temperature decreases. Possible factors to account for this are listed below.

1. Activation Energy for Diffusion

First, there may be a direct effect on the diffusion activation energy, that is, the rate at which atoms jump into and exchange with vacancies in the alloy. The determined activation energy for Al^{26} diffusion in Al is 34 kcal/mole [Ref. 13]. However, most of the values for the activation energy for impurity diffusion in Al are found in the range of 28 to 32 kcal/mole [Ref. 13]. In 8090 and 8091 the diffusivity of Li at 500°C is 2.5×10^{-9} cm²/sec, while that of Al is

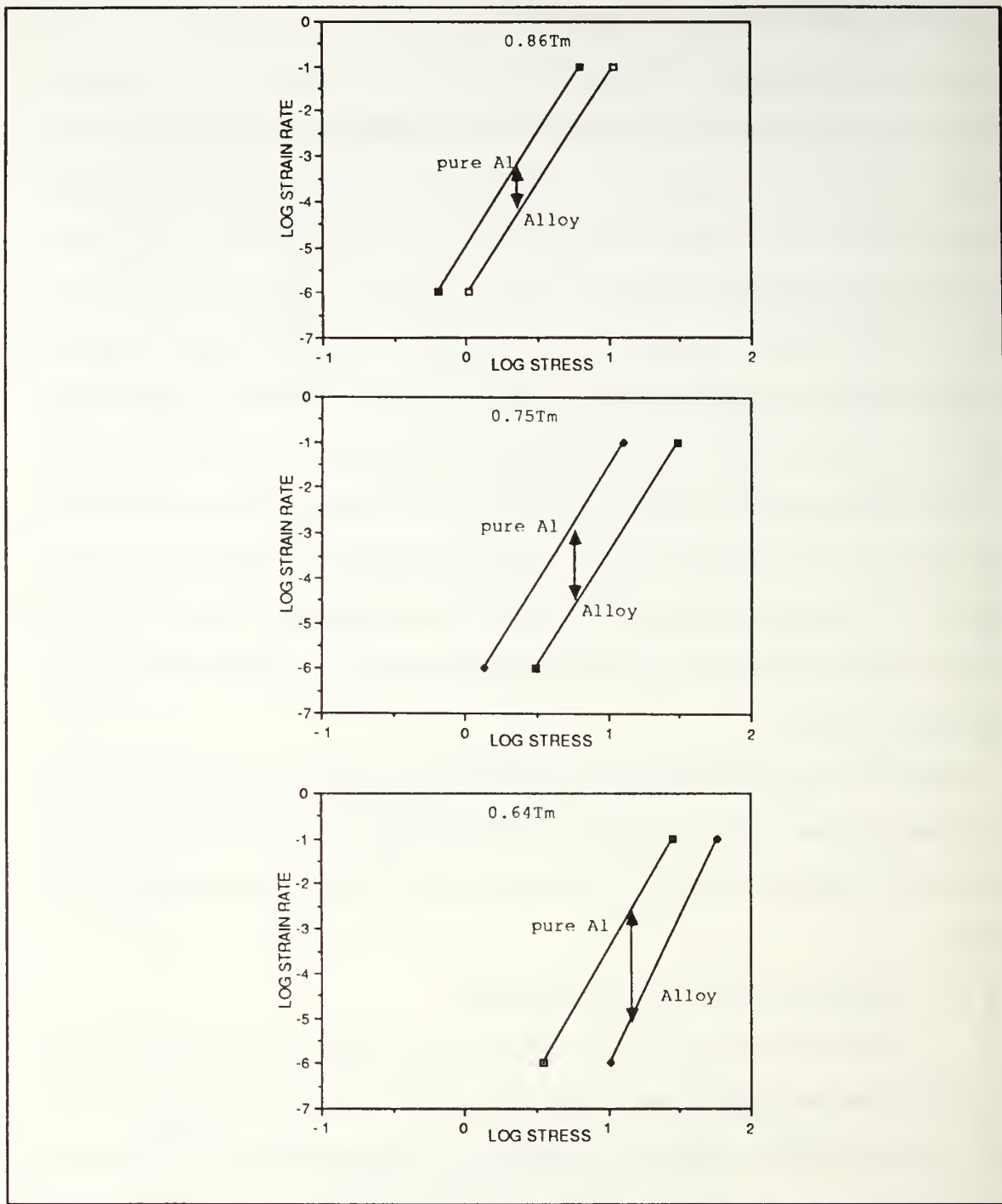


Figure 21. Al-2.0%Li Log $\dot{\epsilon}$ vs. Log σ as Compared to Pure Al:
0.86T_m, 0.75T_m, 0.64T_m

$3.9 \times 10^{-10} \text{ cm}^2/\text{sec}$ [Ref. 14]. These data suggest that the diffusion activation energy for Li in Al is not appreciably different at this temperature.

According to equation 7, the higher activation energy becomes, then the slower $\dot{\epsilon}$ becomes. The present creep data on Al-2.0%Li indicate that Q_c for the alloy is significantly higher than Q_c for the pure metal from 300 to 450°C (47.4 to 54.9 kcal/mole) and then approaches that for Al from 470 to 500°C (40.4 to 33.1 kcal/mole). This explains, in part, why the creep rate of Al-2.0%Li at constant stress and the same homologous temperature is slower than that of the metal.

2. Modulus of Elasticity

In a random solid solution, there is little effect on bonding within the range of the solid solution. Most solid solutions do not show a strong influence on modulus of elasticity with alloy content, since the modulus reflects the way in which the average pair of atoms bond. If, on the other hand, there is an effect directly on the bonding between atoms, as could be reflected in an ordering reaction, causing an increased concentration of Li in the ordered region, an appreciable effect on the modulus of elasticity may be seen.

By equation 7, $\dot{\epsilon}$ is proportional to the modulus-compensated stress, raised to the fifth power, $(\sigma/E)^5$. It is known that the room temperature modulus of elasticity for the alloy is higher than that for pure Al. Each wt.pct. of Li added to Al increases the modulus by 6%, and at room temperature the alloy's modulus of elasticity is reported to be 78.5 GPa [Ref. 15]. By considering the increase in modulus, as a result of the presence of the 2.0% Li in the alloy, then for constant stress, the $\dot{\epsilon}$ of Al-2.0%Li would be slower than that of Al.

It is also known that for any pure metal or simple alloy that the modulus of elasticity, overall, decreases with temperature. It is postulated, based on the work of Fox and Fisher[Ref. 2] and on the work of Radmilovic *et al* [Ref. 3], that within the range of the solid solution, there is a tendency of the Li to form an ordered structure. Thus, the modulus of elasticity may exhibit a more rapid decrease with increasing temperature than does the modulus of pure Al at temperatures below, but near, the ordering temperature (expected to be ~700K based on the data of this research).

If it is assumed that this apparent increase in activation energy is associated with the modulus of elasticity alone, then it is postulated that the elastic modulus as a function of temperature for the alloy, might appear as shown in Figure 22. On this figure, the data for the modulus of pure Al is shown by the solid line. The data for the modulus of the alloy is available at room temperature (300K) and is 78.5 GPa [Ref. 15]. The modulus of the alloy at the melting point was calculated using the following relationship [Ref. 2]:

$$E = K\mu\theta^2 \quad (12)$$

where K is a physical constant, μ is the average mass of the alloy and θ is the Debye temperature. The temperature at the melting point of the alloy is 901K and the calculated modulus of elasticity is 37 GPa. The observed effect upon the activation energy would arise if the alloy's modulus were to decrease with temperature as shown by the dashed line. In the temperature interval of 600 to 720K, the alloy has a steeper, more negative slope as a result of disorder through heating, or conversely, ordering upon cooling. The slope associated with the triangle represents a variation of modulus with temperature sufficient to account

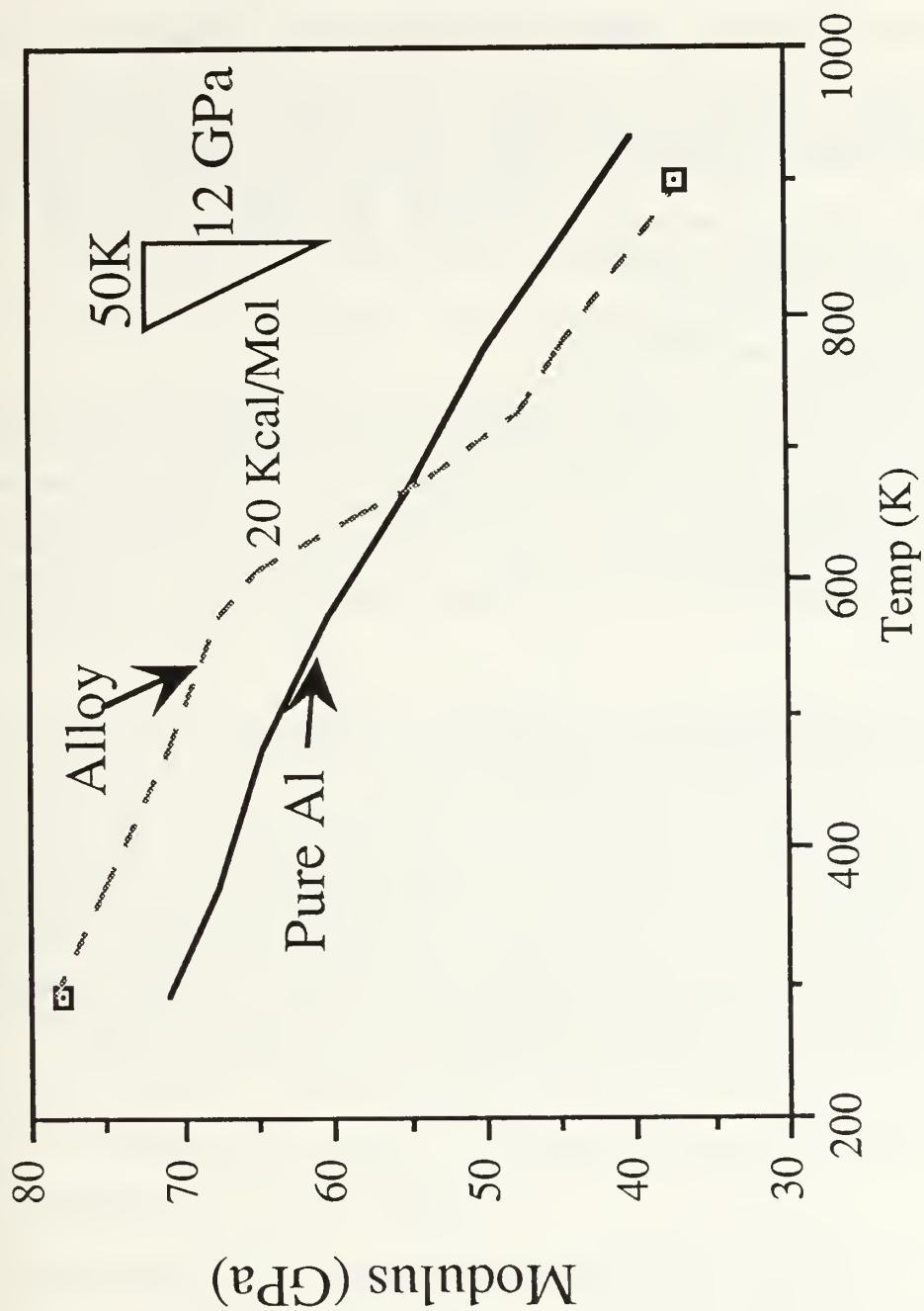


Figure 22. Proposed Modulus of Elasticity as a Function of Temperature

for an increase in the creep activation energy from a value of 34 kcal/mole (associated with diffusion only), to a value of 55 kcal/mole (as observed experimentally). This slope was calculated using equation 10. Without using the Debye temperature, the proposed modulus of the alloy is expected to decrease to values below the modulus of pure Al because the melting temperature of the alloy is less than for the metal.

3. Stacking Fault Energy

It was shown in Chapter II that under the condition of climb control, the creep rate is described by equation 7 and that the creep rate is proportional to the cube of the stacking fault energy, $(\gamma)^3$. This suggests that if the γ of the alloy is lower than that of Al then, at constant stress, the creep rate will be slower than that of Al.

The ordering reaction could also have an influence on the stacking fault energy. In the case of pure Al, the best evidence is that, essentially, there is no effect of temperature on stacking fault energy. The effect of Li upon the stacking fault energy of Al is not known. It is acknowledged that in the search for accurate physical models, the stacking fault energy is a difficult quantity to measure, and there are no data in the literature that are widely accepted.

V. CONCLUSIONS

The following conclusions can be drawn concerning the behavior and characteristics of the binary alloy Al-2.0%Li:

1. Al-2.0%Li exhibits a creep response consisting of a pronounced primary, a secondary, and a tertiary phase. This characteristic curve shape is similar to that for pure Al and demonstrates that the steady-state creep behavior of the class II Al-2.0%Li alloy (metal class) is controlled by some form of dislocation climb.

2. Considering the stress dependence of each corresponding strain rate, the stress exponent, n , varies from ~ 6.7 at 300°C to ~ 4.9 at 500°C , and is similar to that reported for Al ($n \sim 5$).

3. Al-2.0%Li data at 500°C correspond to within a factor of 2 to data reported by Park *et al* for a similar alloy using double shear creep testing.

4. Activation energy obtained for Al-2.0%Li from isothermal creep and from temperature cycling testing indicates an anomalously high activation energy from 300°C to 450°C . Activation energy for creep reaches a maximum value of 55 kcal/mole, a difference of about 20kcal/mole higher than that for Al at a temperature of 400°C . This may result from the temperature-dependence of modulus or stacking fault energy or through additional processes such as ordering of the Li in the solid solution.

5. For the same homologous temperature the creep strength of Al-2.0%Li is higher than that of Al; a possible decrease in the stacking fault energy combined with a measured increase in the activation energy for creep in Al with the addition of Li may responsible for this finding.

VI. RECOMENDATIONS

1. Investigate alternative methods to assess the order/disorder reaction.
2. Determine modulus as a function of temperature using ultrasonic vibration methods.
3. Investigate microstructure with Transmission Electron Microscopy (TEM).
4. Investigate the effects of various elements in an Al-Li-X.

APPENDIX A. STRESS STRAIN CURVES

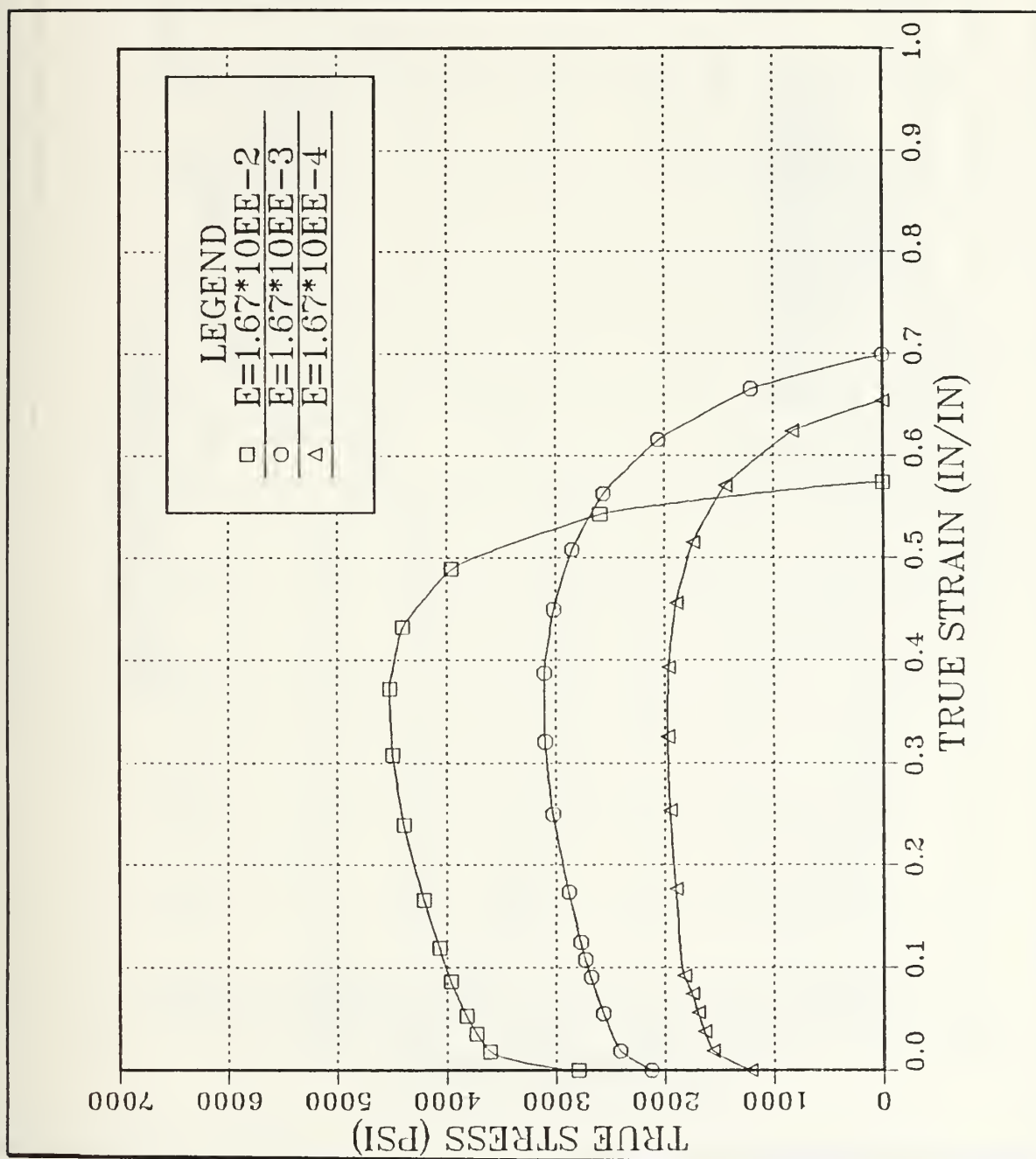


Figure 22. Stress Strain Curves at 350°C for Various Strain Rates

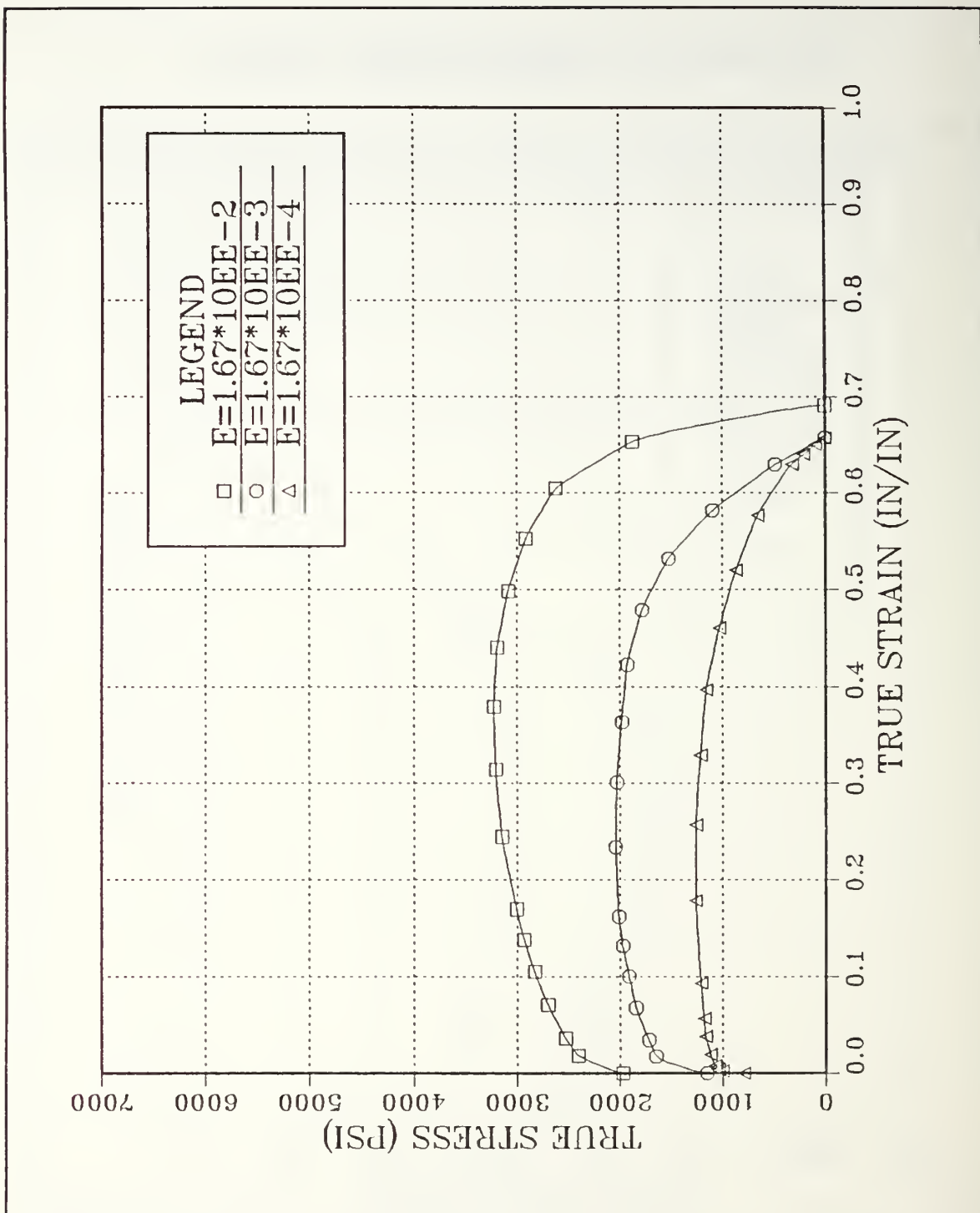


Figure 23. Stress Strain Curves at 400°C for Various Strain Rates

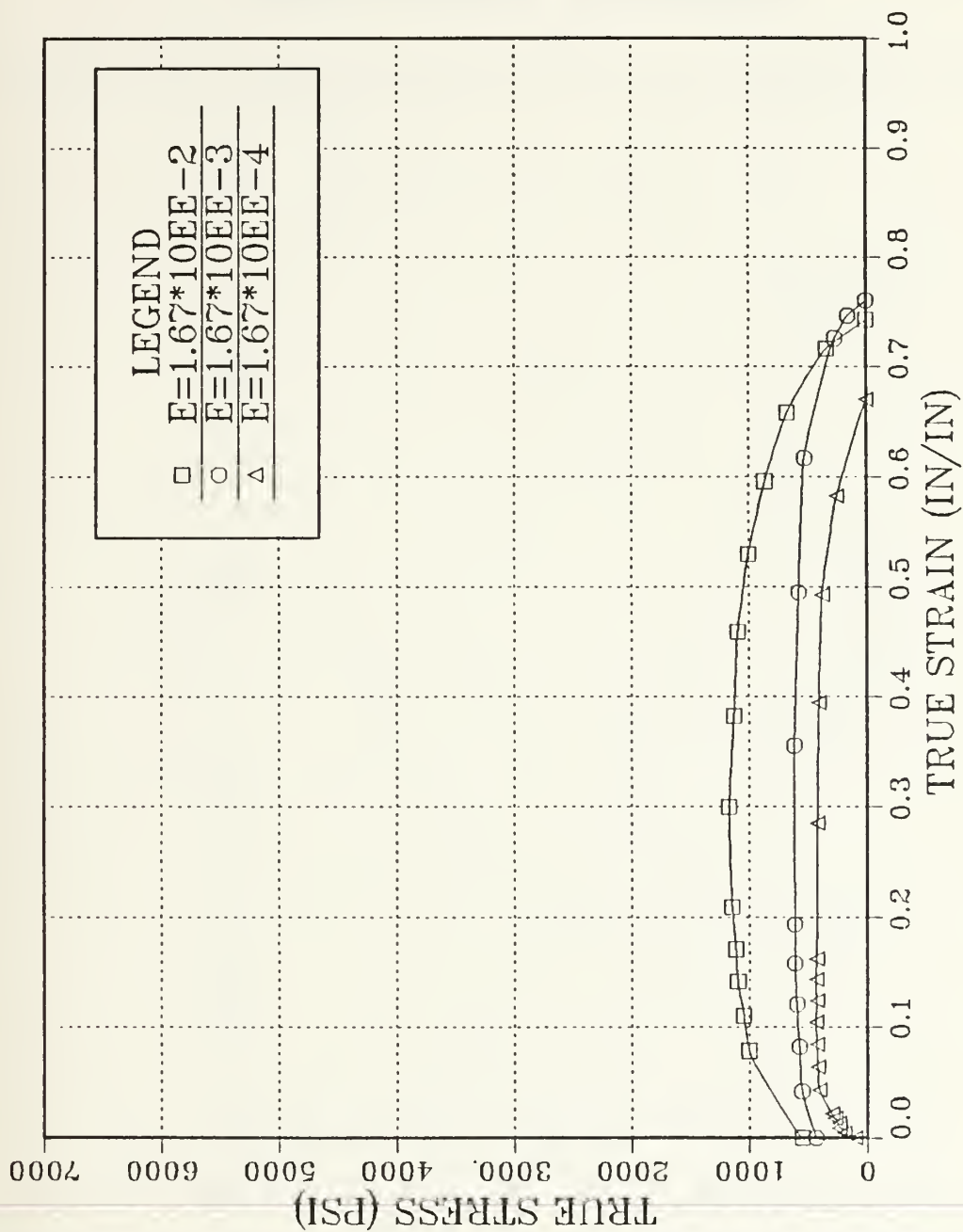


Figure 24. Stress Strain Curves at 500°C for Various Strain Rates

APPENDIX B. CREEP CURVES

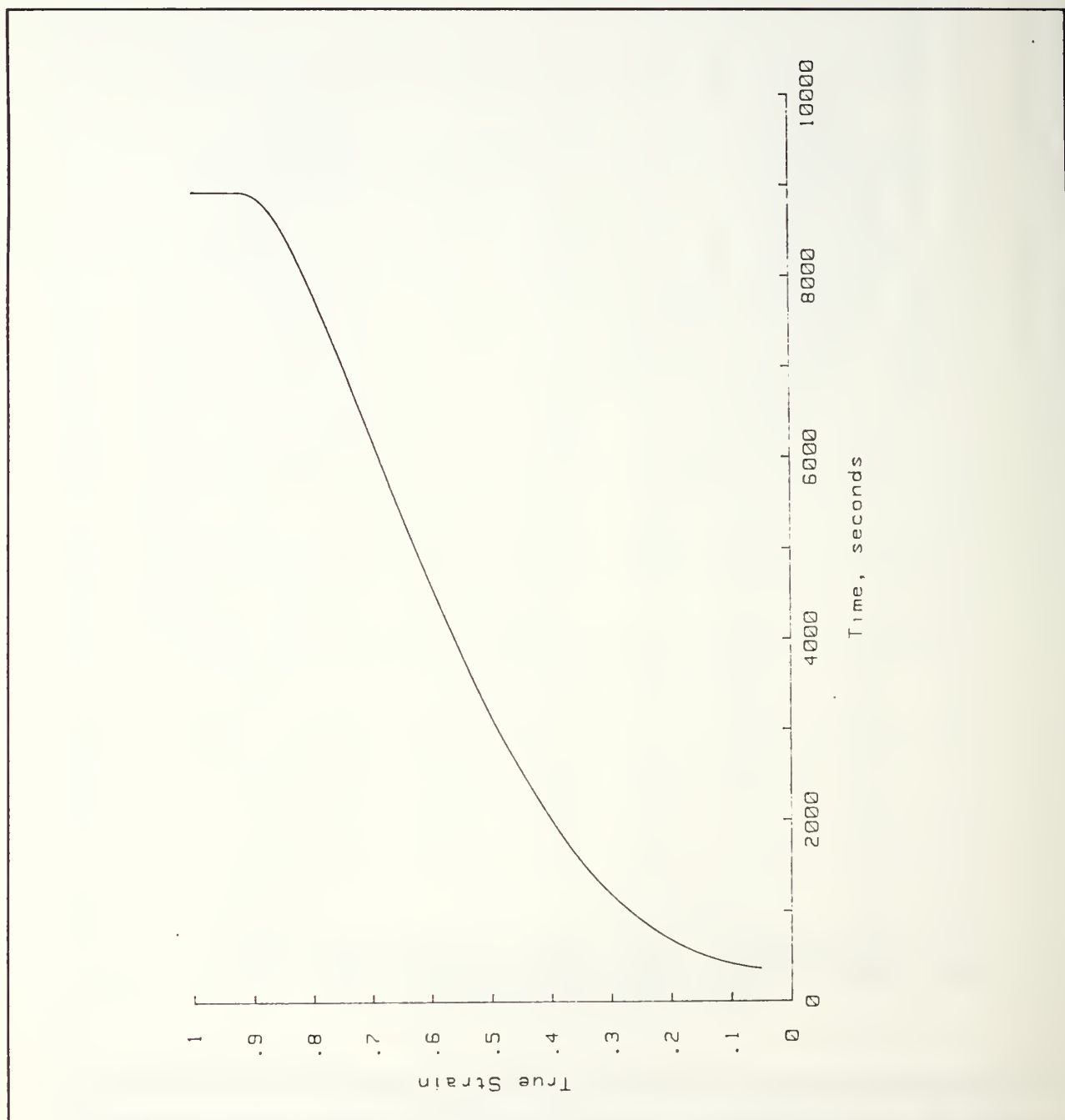


Figure 25. Creep Curve at 300°C for a Stress of 21.2 MPa:

$$\dot{\epsilon}_{\min} = 6.40 \times 10^{-5} \text{ sec}^{-1}$$

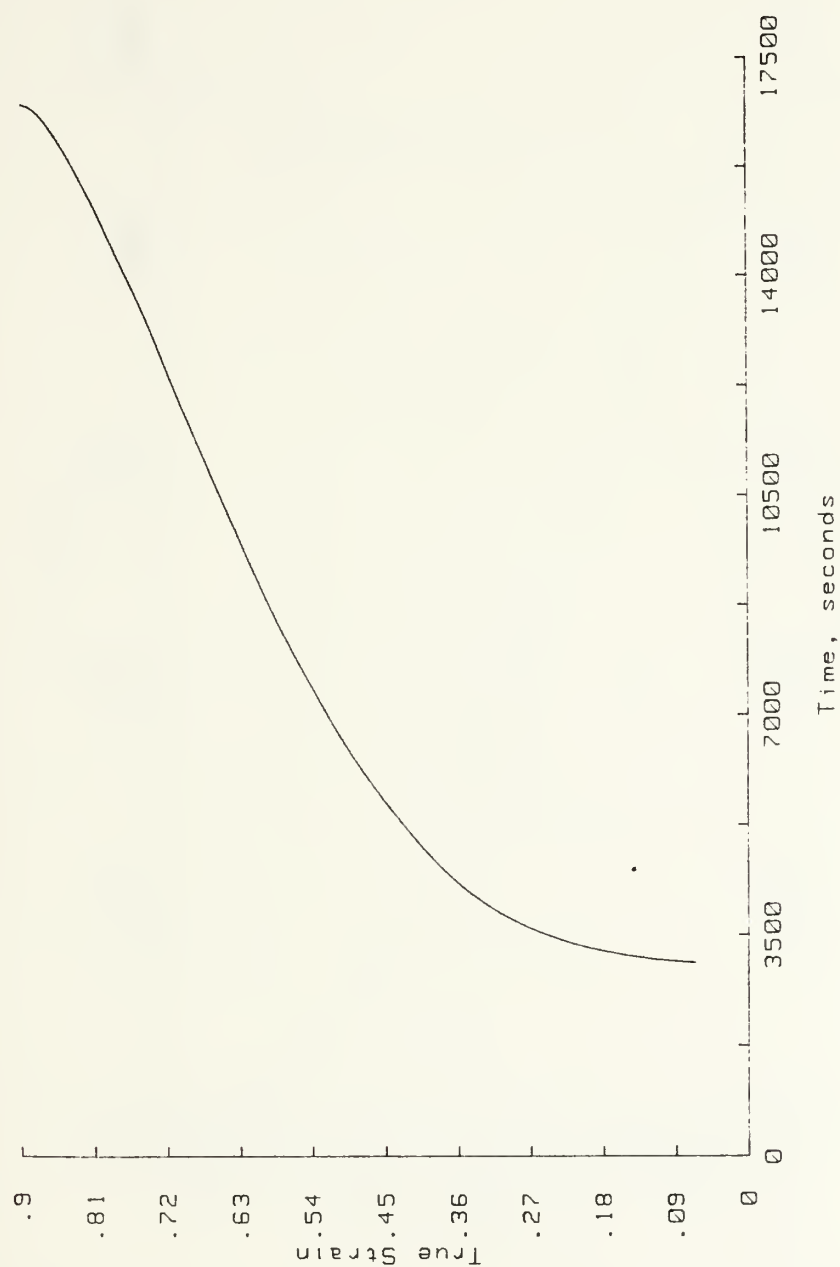


Figure 26. Creep Curve at 300°C for a Stress of 19.0 MPa:

$$\dot{\epsilon}_{\min} = 3.25 \times 10^{-5} \text{ sec}^{-1}$$

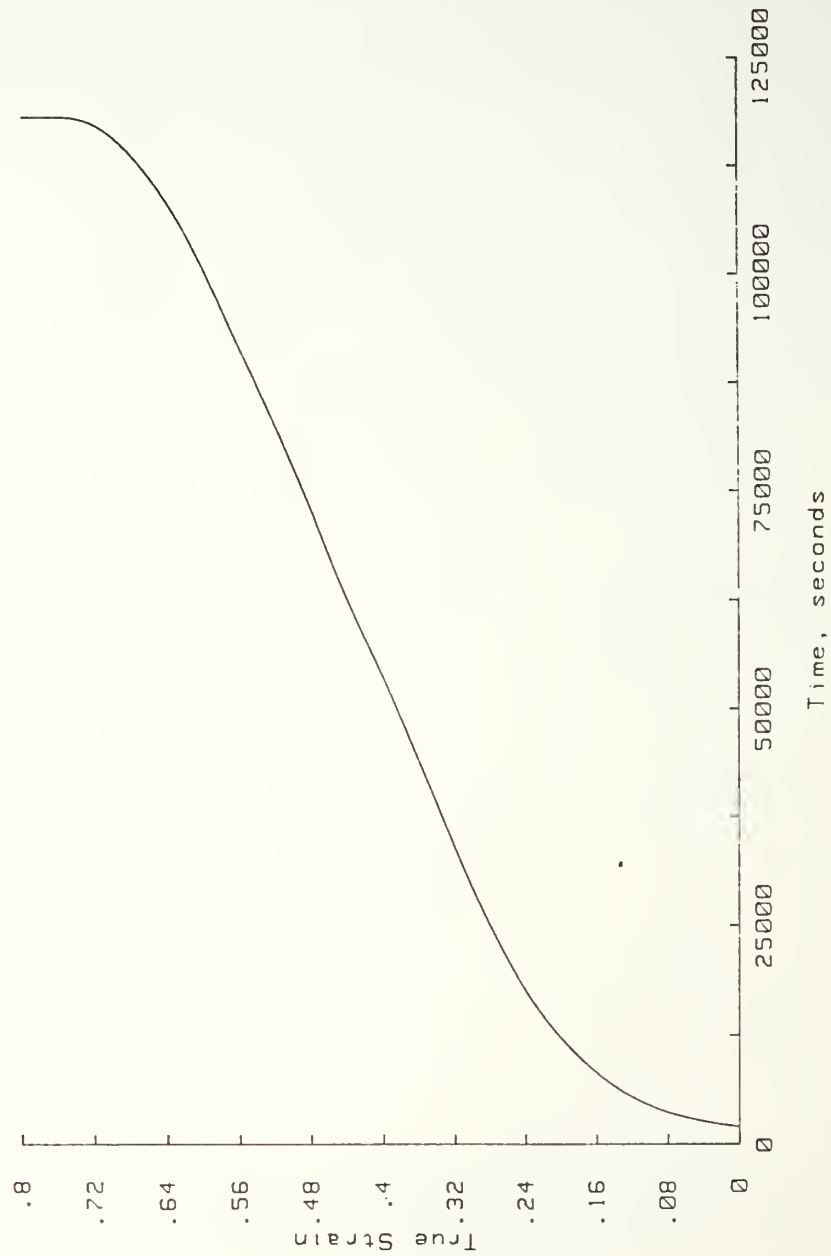


Figure 27. Creep Curve at 300°C for a Stress of 13.0 MPa:

$$\dot{\epsilon}_{\min} = 4.24 \times 10^{-6} \text{ sec}^{-1}$$

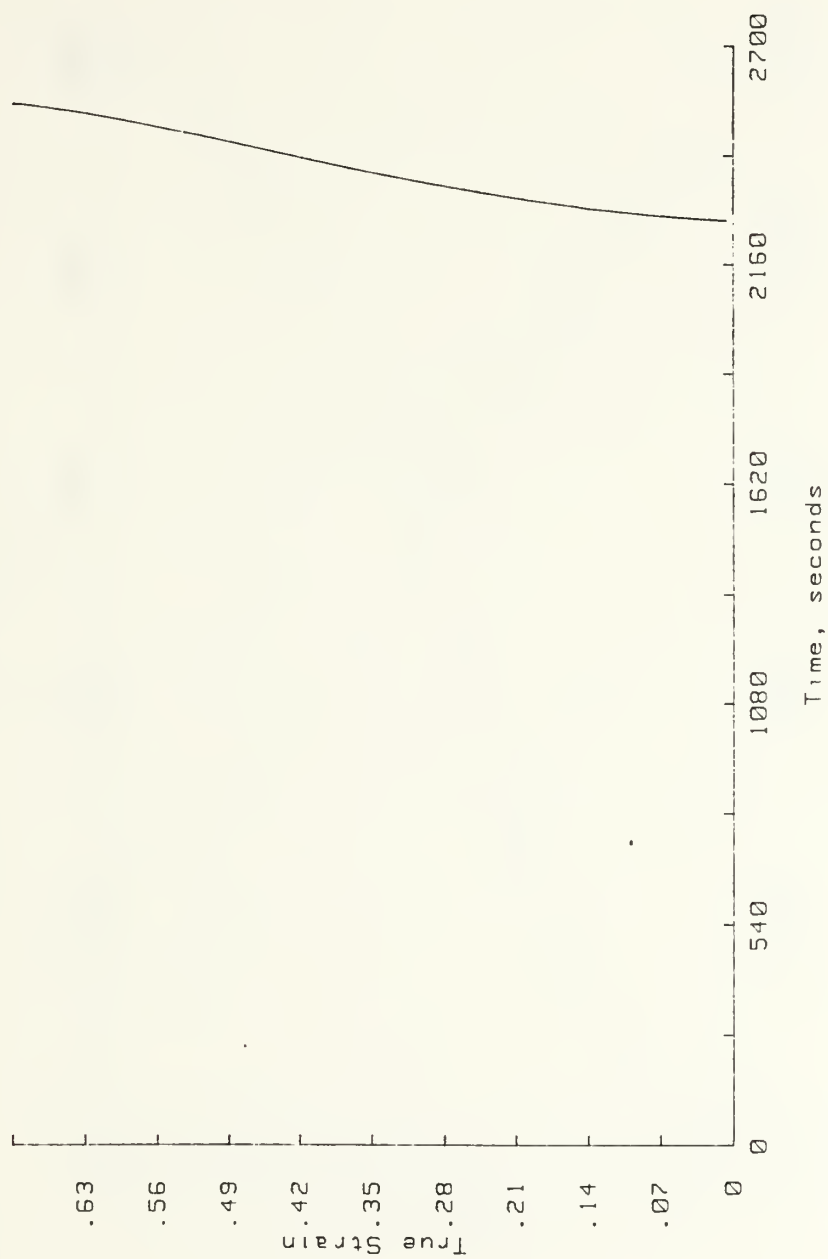


Figure 28. Creep Curve at 350°C for a Stress of 21.2 MPa:

$$\dot{\epsilon}_{\min} = 1.90 \times 10^{-3} \text{ sec}^{-1}$$

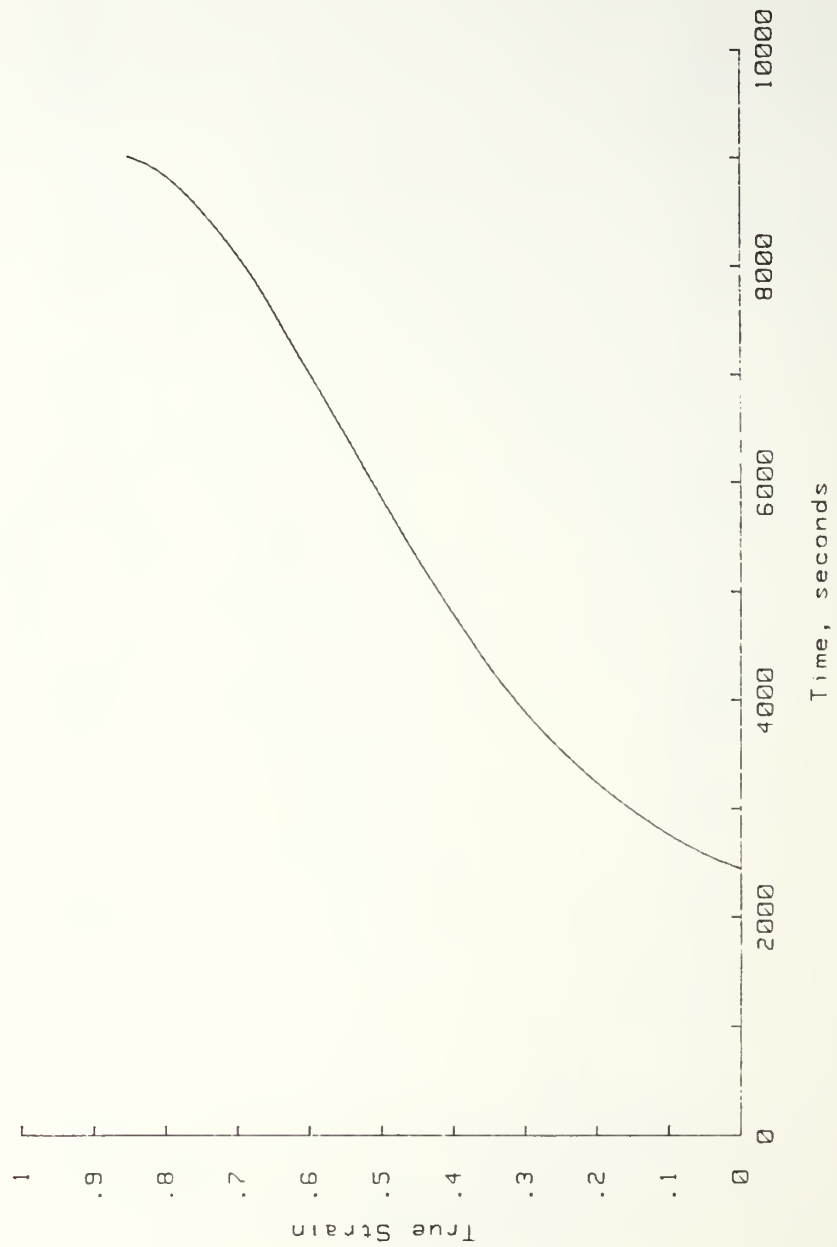


Figure 29. Creep Curve at 350°C for a Stress of 12.9 MPa:

$$\dot{\epsilon}_{\min} = 8.88 \times 10^{-5} \text{ sec}^{-1}$$

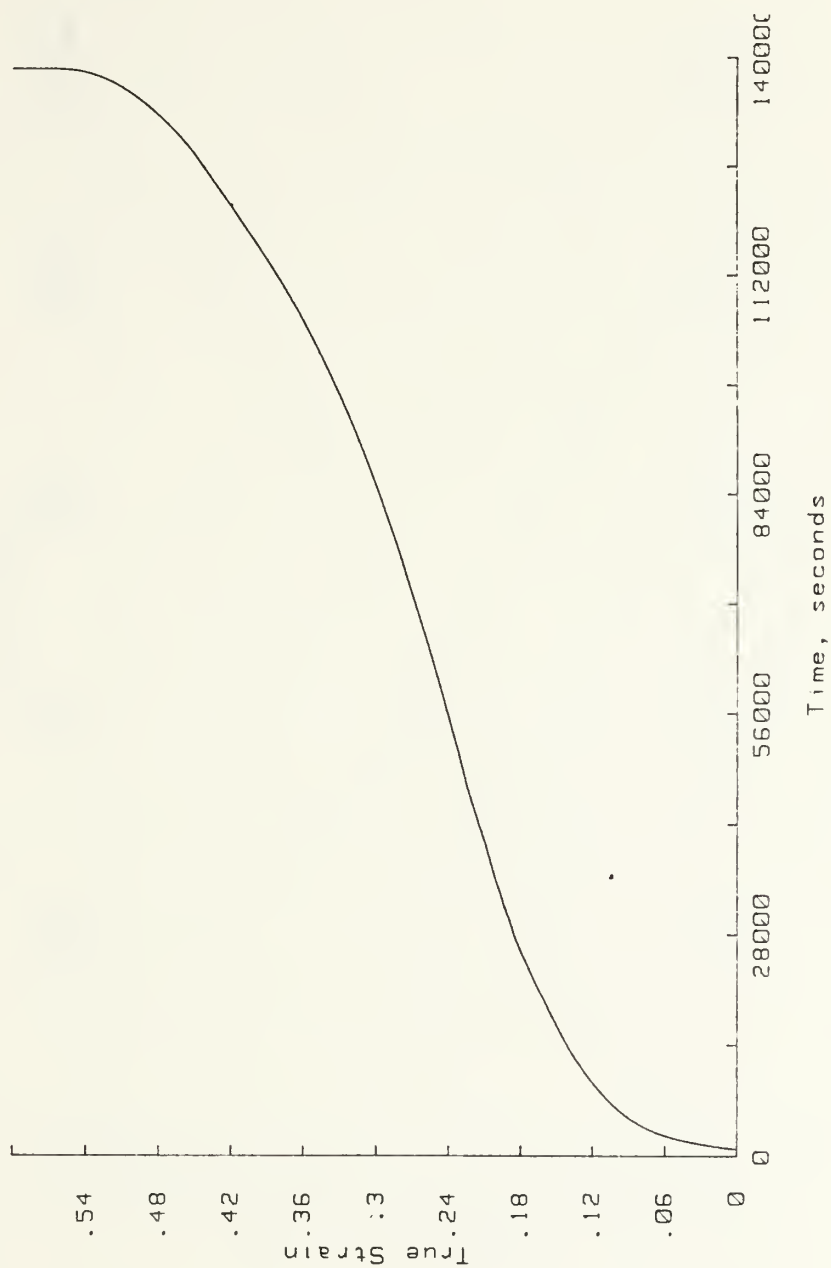


Figure 30. Creep Curve at 350°C for a Stress of 7.00 MPa:

$$\dot{\epsilon}_{\min} = 1.93 \times 10^{-6} \text{ sec}^{-1}$$

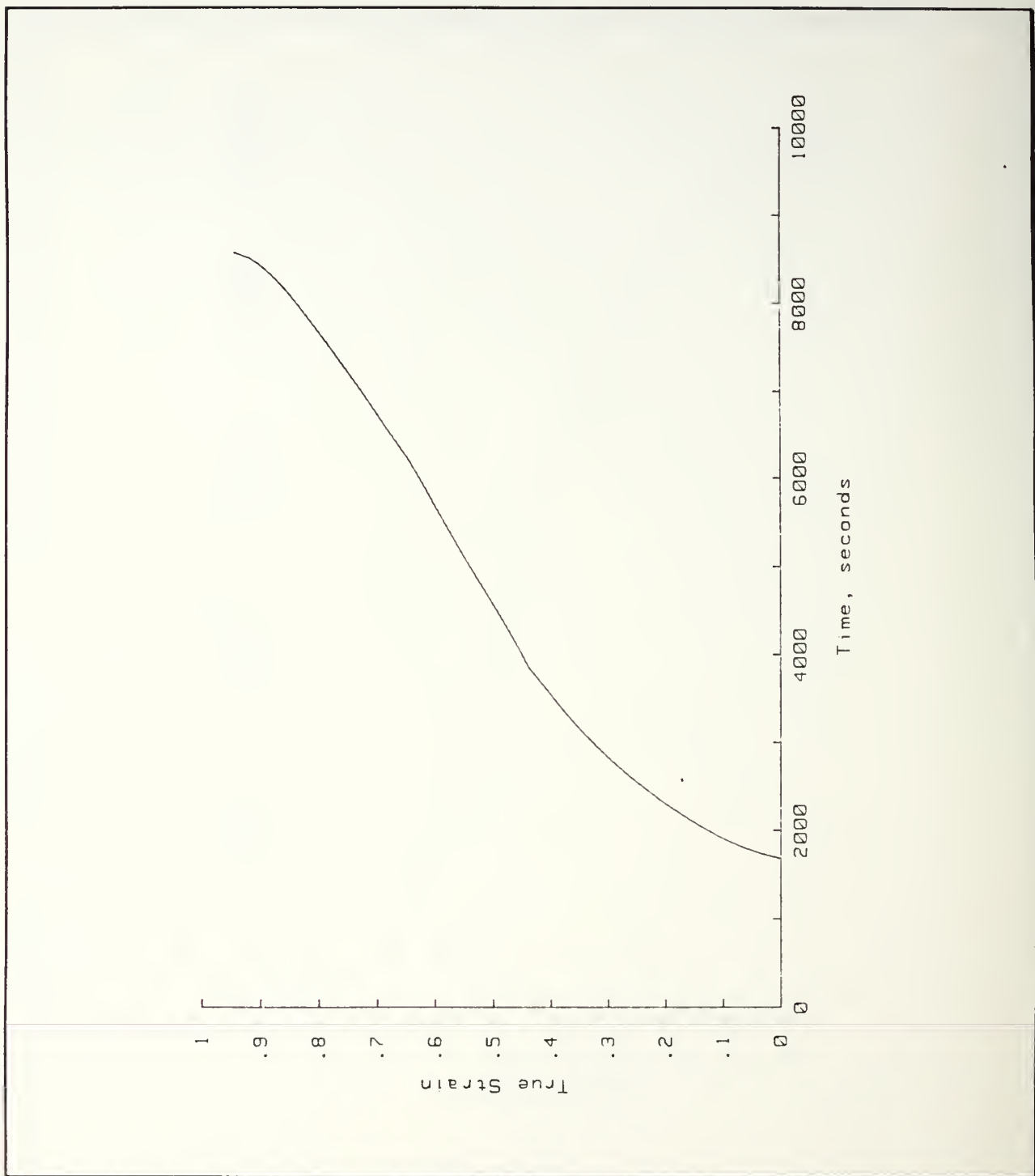


Figure 31. Creep Curve at 400°C for a Stress of 7.10 MPa:

$$\dot{\epsilon}_{\min} = 9.00 \times 10^{-5} \text{ sec}^{-1}$$

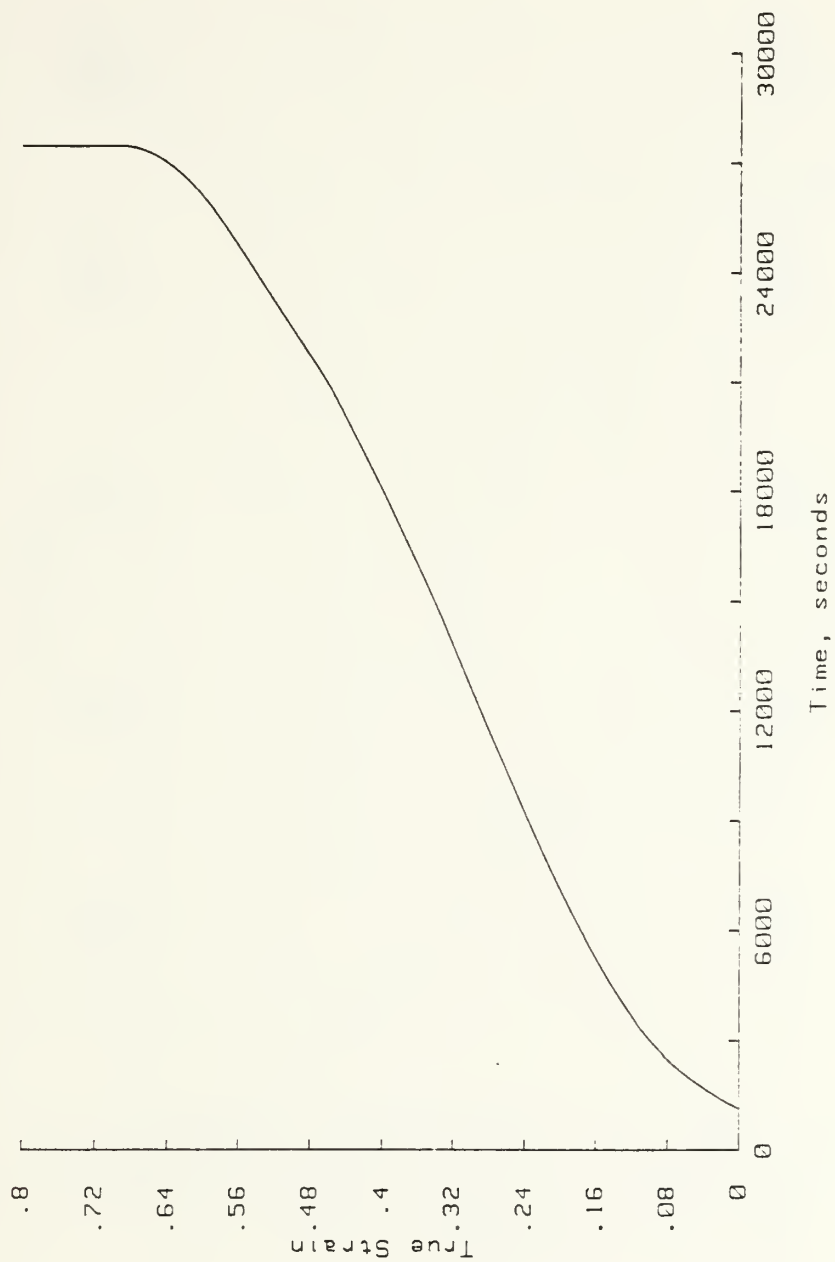


Figure 32. Creep Curve at 400°C for a Stress of 5.27 MPa:

$$\dot{\epsilon}_{\min} = 1.71 \times 10^{-5} \text{ sec}^{-1}$$

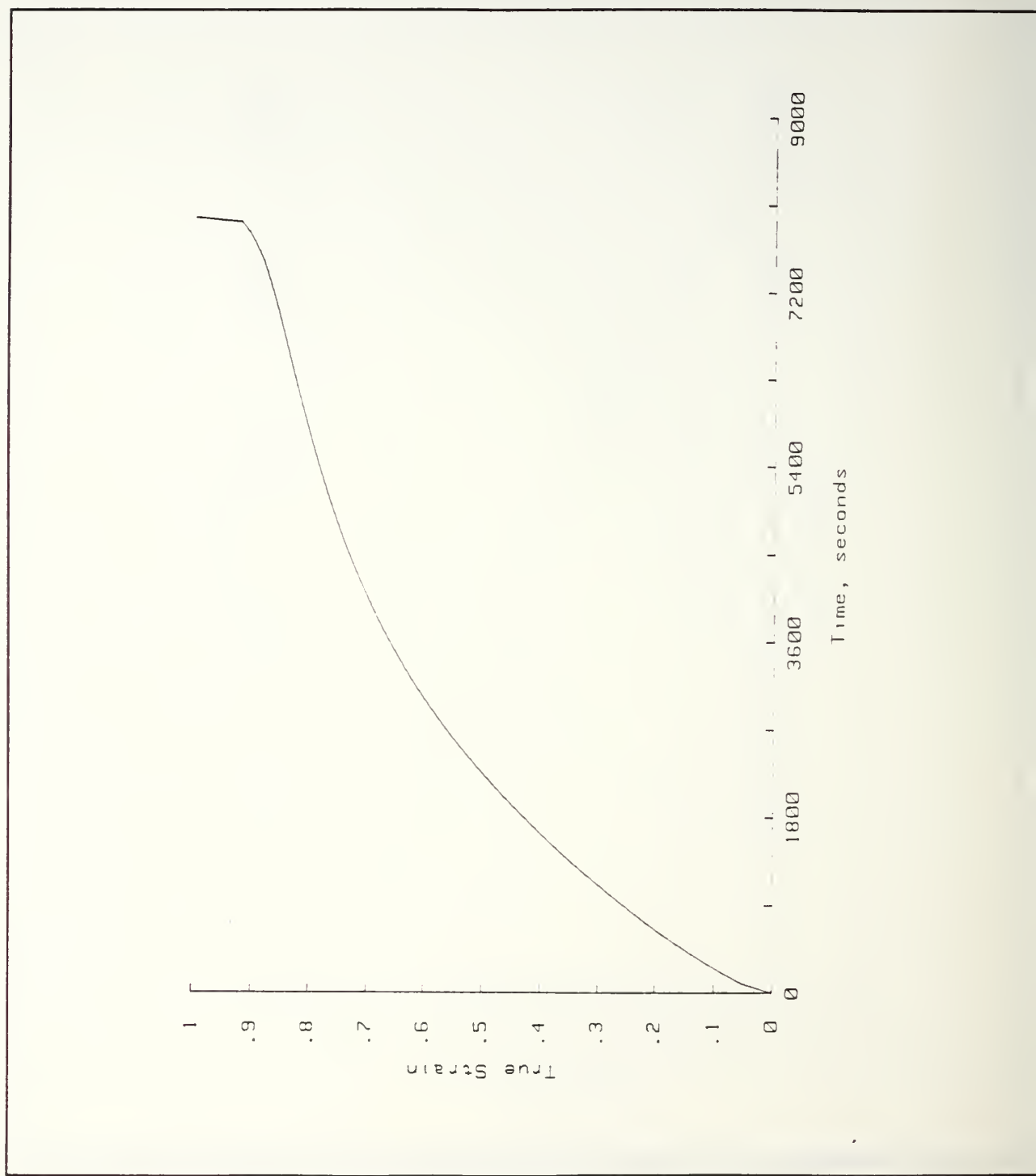


Figure 33. Creep Curve at 450°C for a Stress of 2.35 MPa:

$$\dot{\epsilon}_{\min} = 4.43 \times 10^{-5} \text{ sec}^{-1}$$

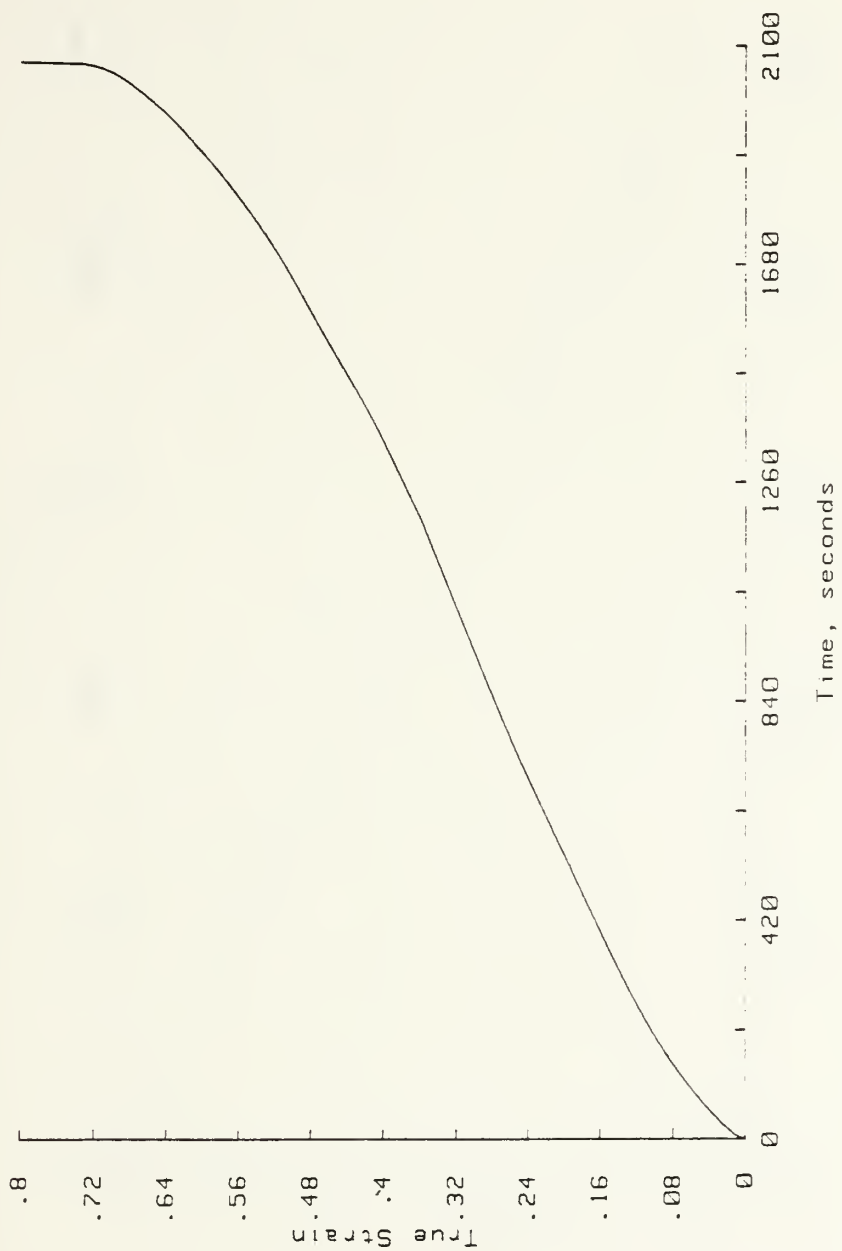


Figure 34. Creep Curve at 500°C for a Stress of 3.02 MPa:

$$\dot{\epsilon}_{\min} = 2.43 \times 10^{-4} \text{ sec}^{-1}$$

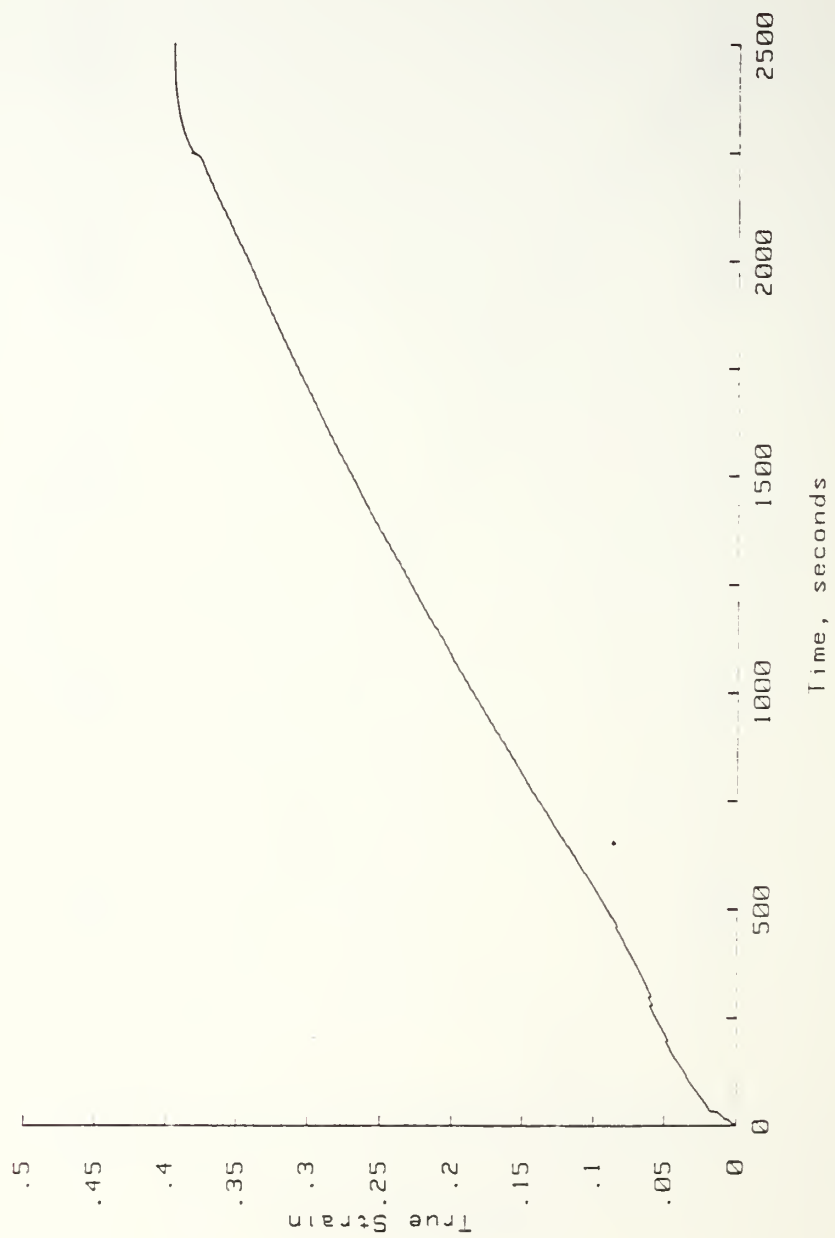


Figure 35. Creep Curve at 500°C for a Stress of 2.65 MPa:

$$\dot{\epsilon}_{\min} = 1.49 \times 10^{-4} \text{ sec}^{-1} \text{ (Arrested Test)}$$

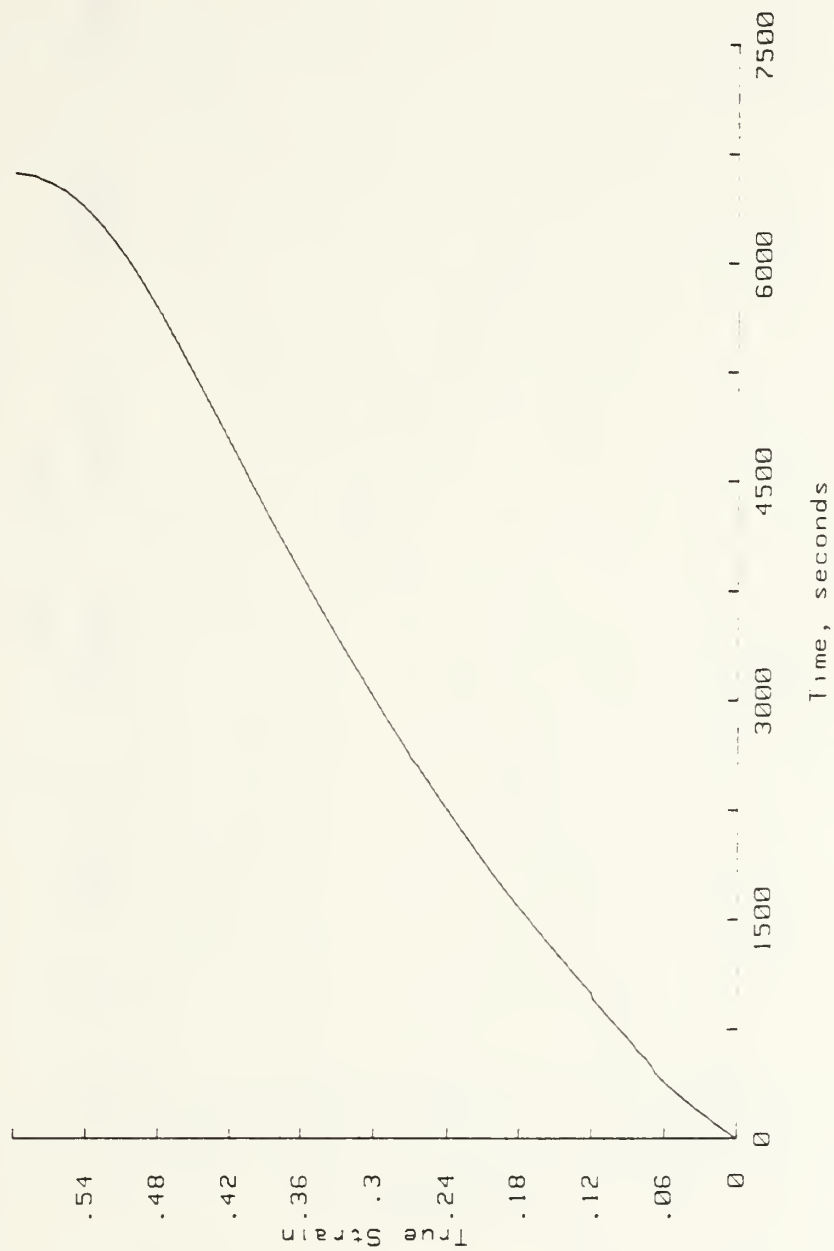


Figure 36. Creep Curve at 500°C for a Stress of 2.25 MPa:

$$\dot{\epsilon}_{\min} = 6.59 \times 10^{-5} \text{ sec}^{-1}$$

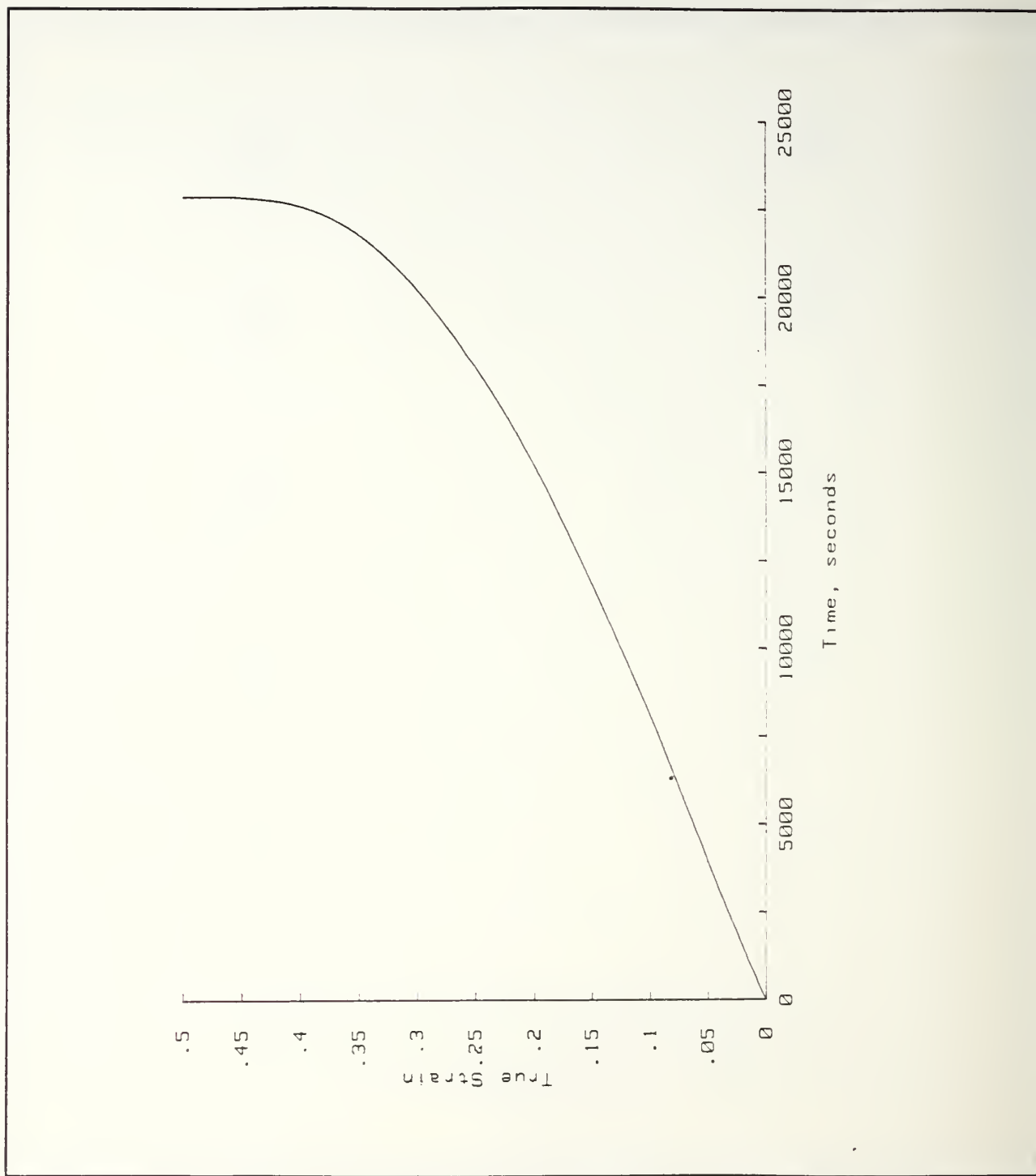


Figure 37. Creep Curve at 500°C for a Stress of 1.84 MPa:

$$\dot{\epsilon}_{\min} = 1.20 \times 10^{-5} \text{ sec}^{-1}$$

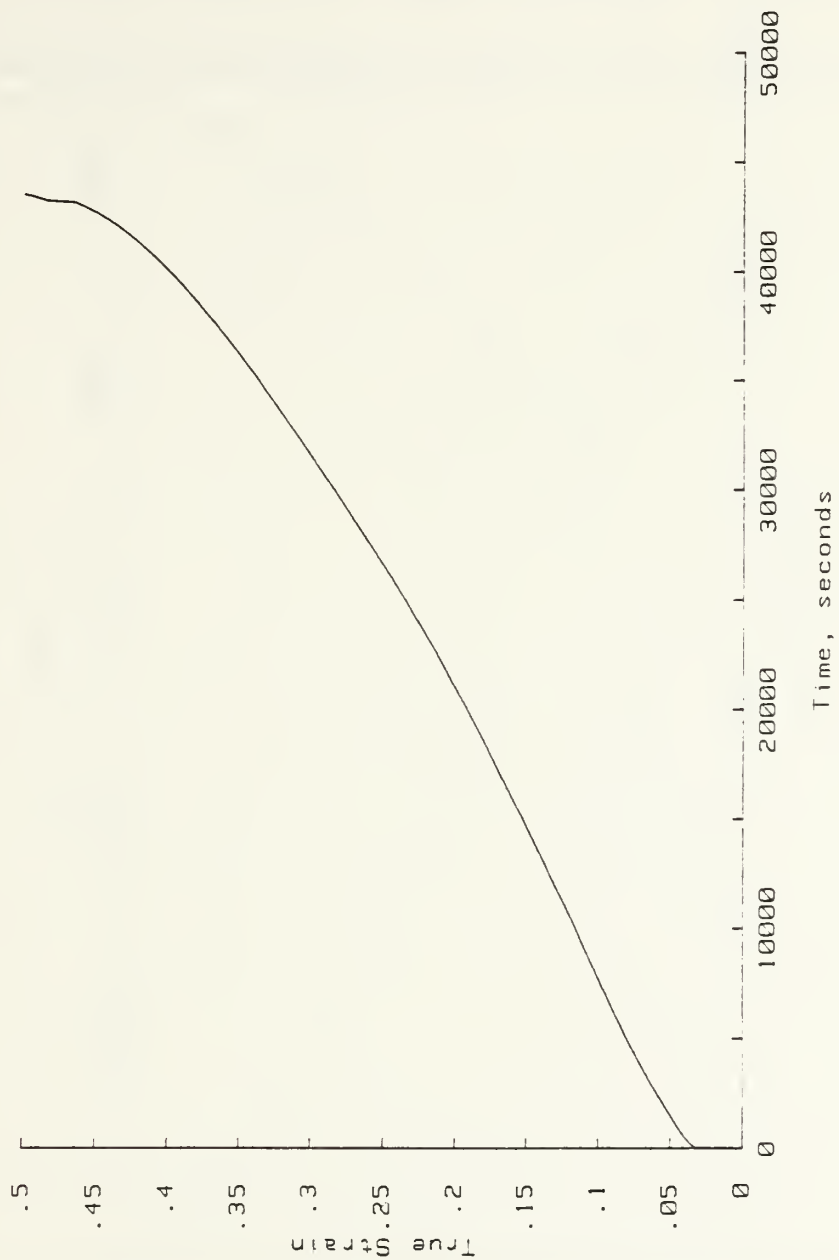


Figure 38. Creep Curve at 500°C for a Stress of 1.63 MPa:

$$\dot{\epsilon}_{\min} = 6.00 \times 10^{-6} \text{ sec}^{-1}$$

APPENDIX C. TEMPERATURE CYCLING CREEP CURVES

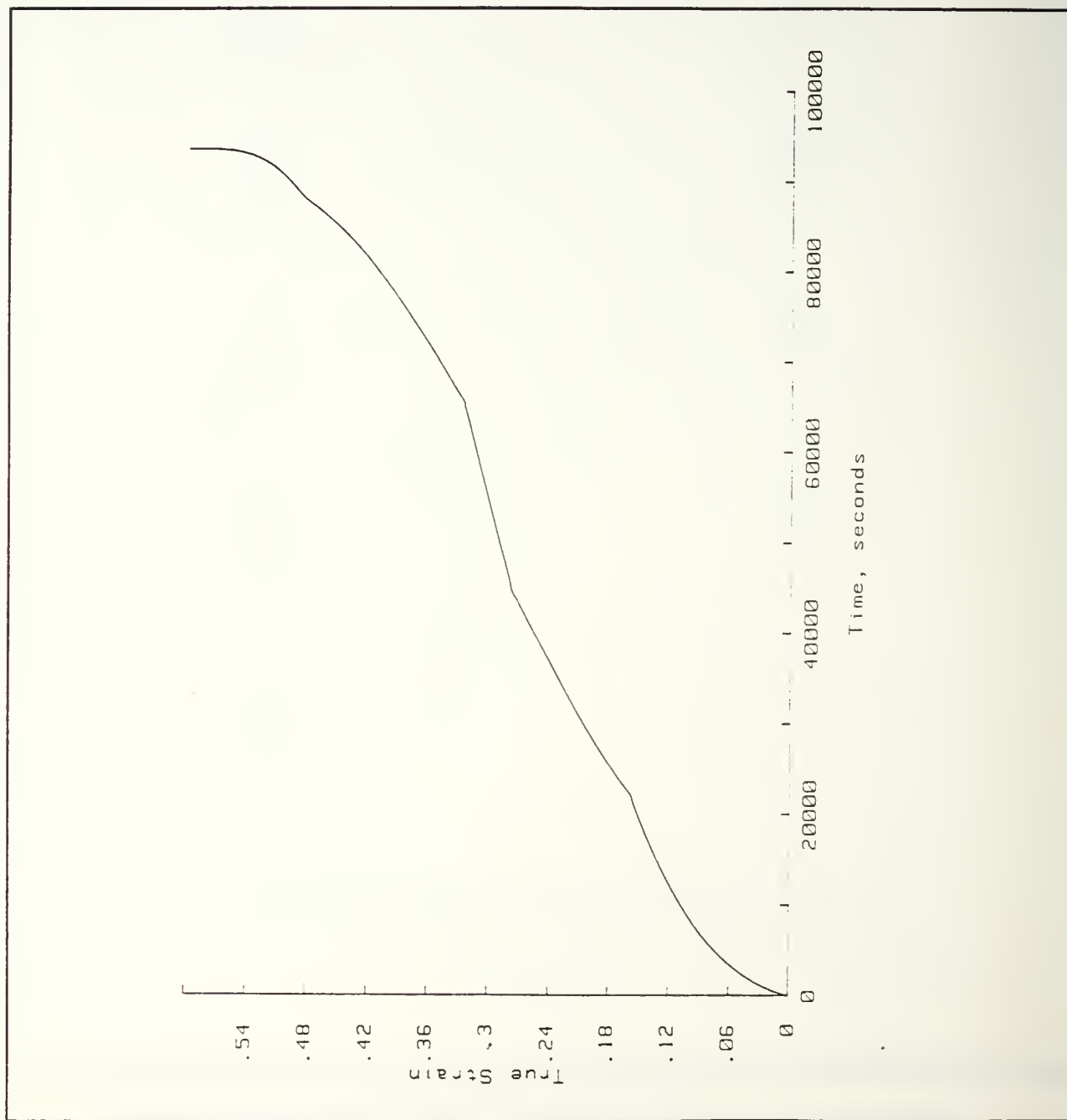


Figure 39. Creep Curve at 300-310°C for a Stress of 11.9 MPa:

$$\dot{\epsilon}_1 = 2.10 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 4.30 \times 10^{-6} \text{ sec}^{-1}$$

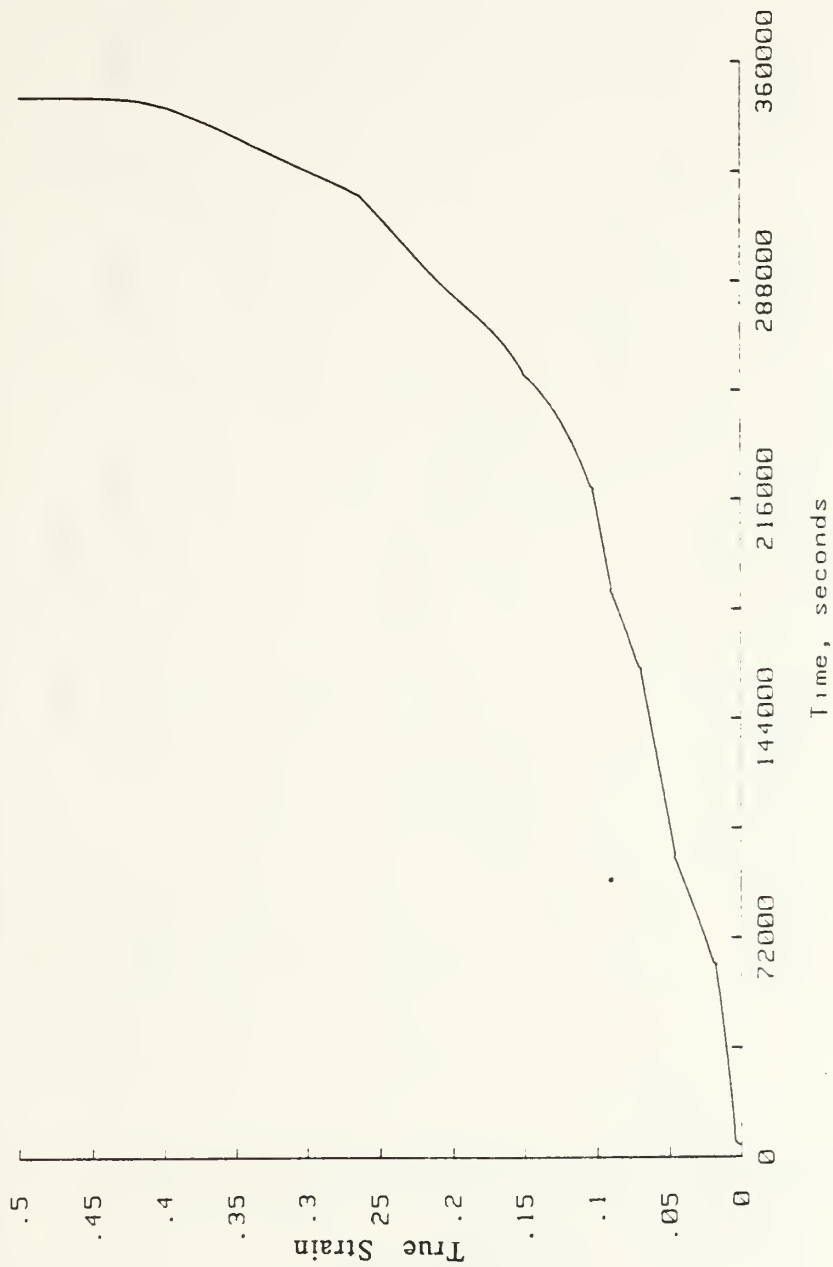


Figure 40. Creep Curve at 400-410°C for a Stress of 3.03 MPa:

$$\dot{\epsilon}_1 = 3.98 \times 10^{-7} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 7.31 \times 10^{-7} \text{ sec}^{-1}$$

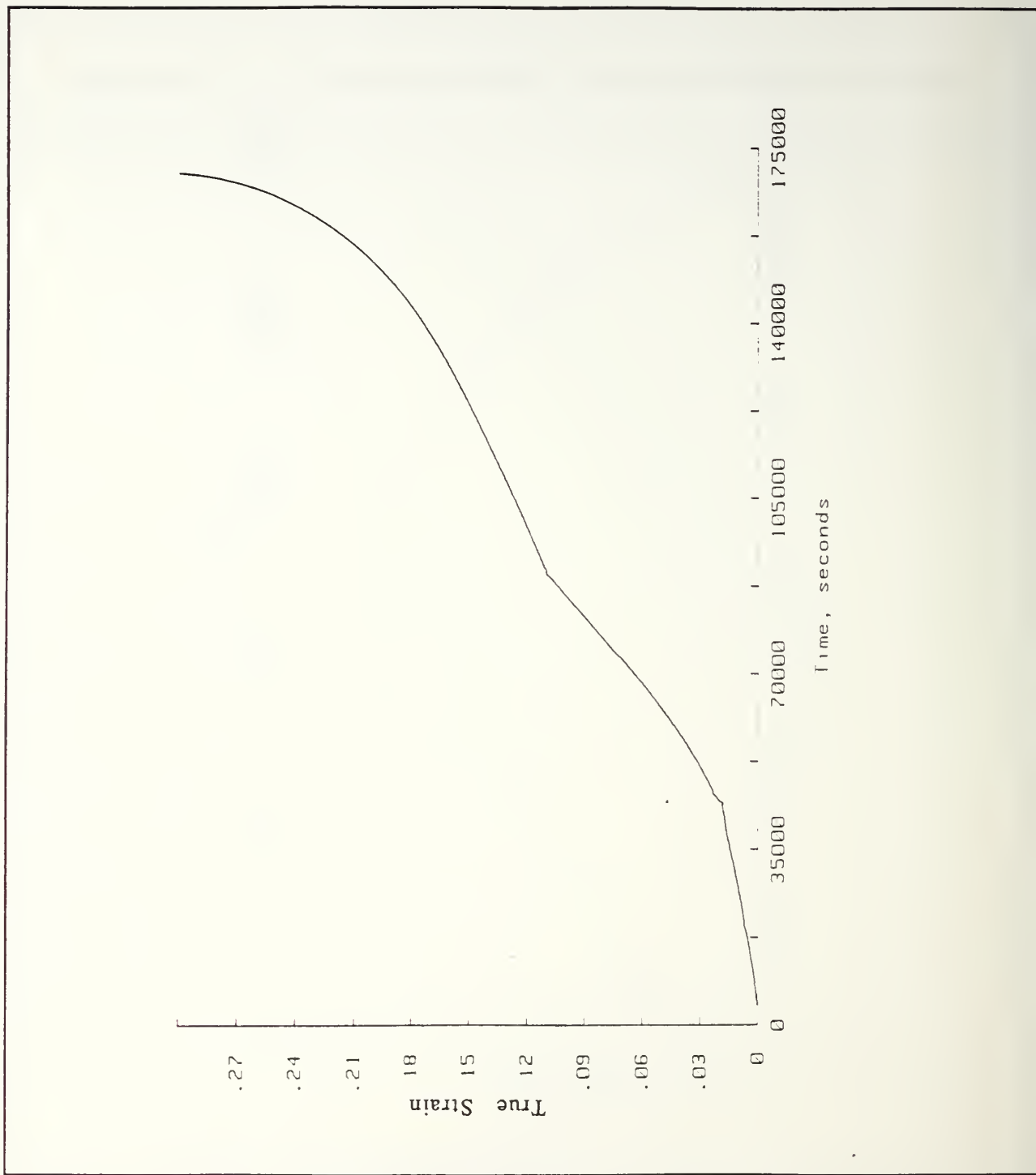


Figure 41. Creep Curve at 400-410°C for a Stress of 3.03 MPa:

$$\dot{\epsilon}_1 = 1.18 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 2.22 \times 10^{-6} \text{ sec}^{-1}$$

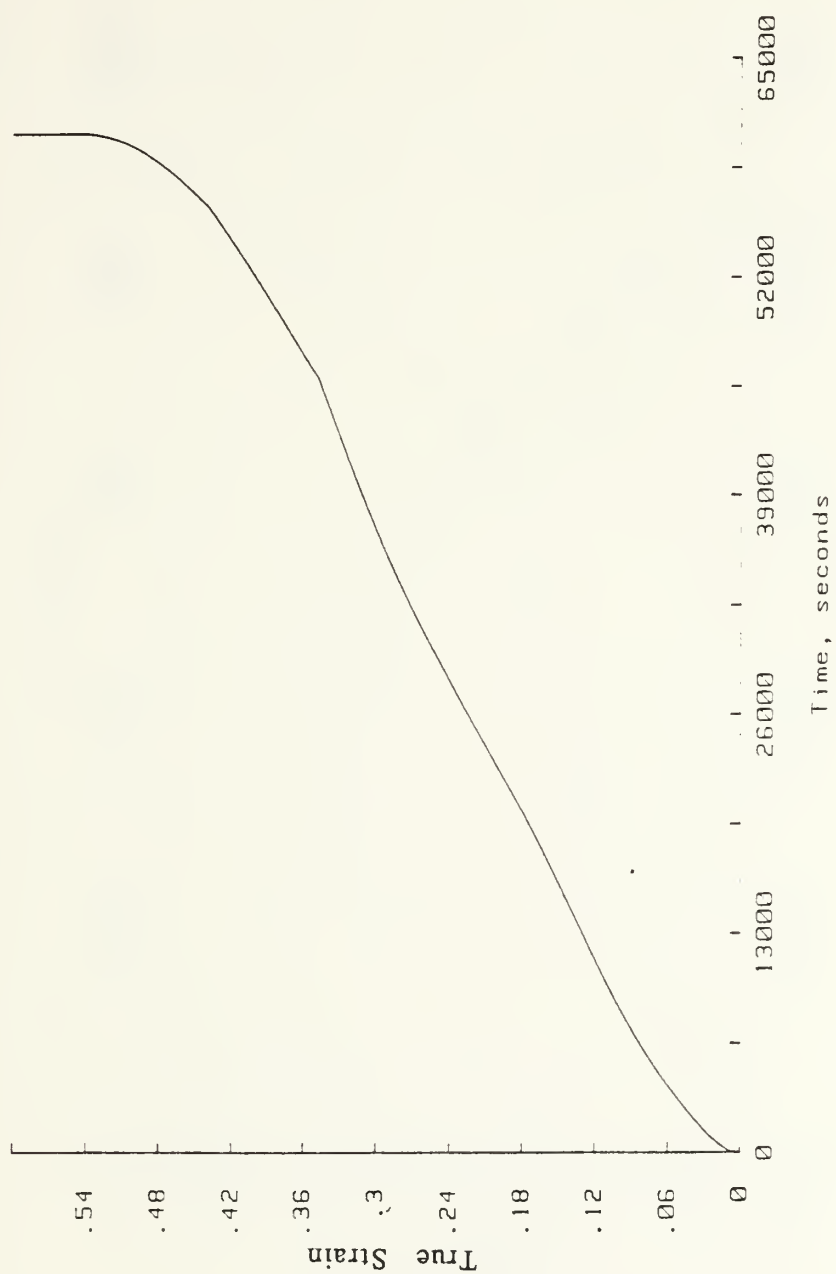


Figure 42. Creep Curve at 450-460°C for a Stress of 2.46 MPa:

$$\dot{\epsilon}_1 = 5.15 \times 10^{-6} \text{ sec}^{-1} \text{ \& } \dot{\epsilon}_2 = 8.69 \times 10^{-6} \text{ sec}^{-1}$$

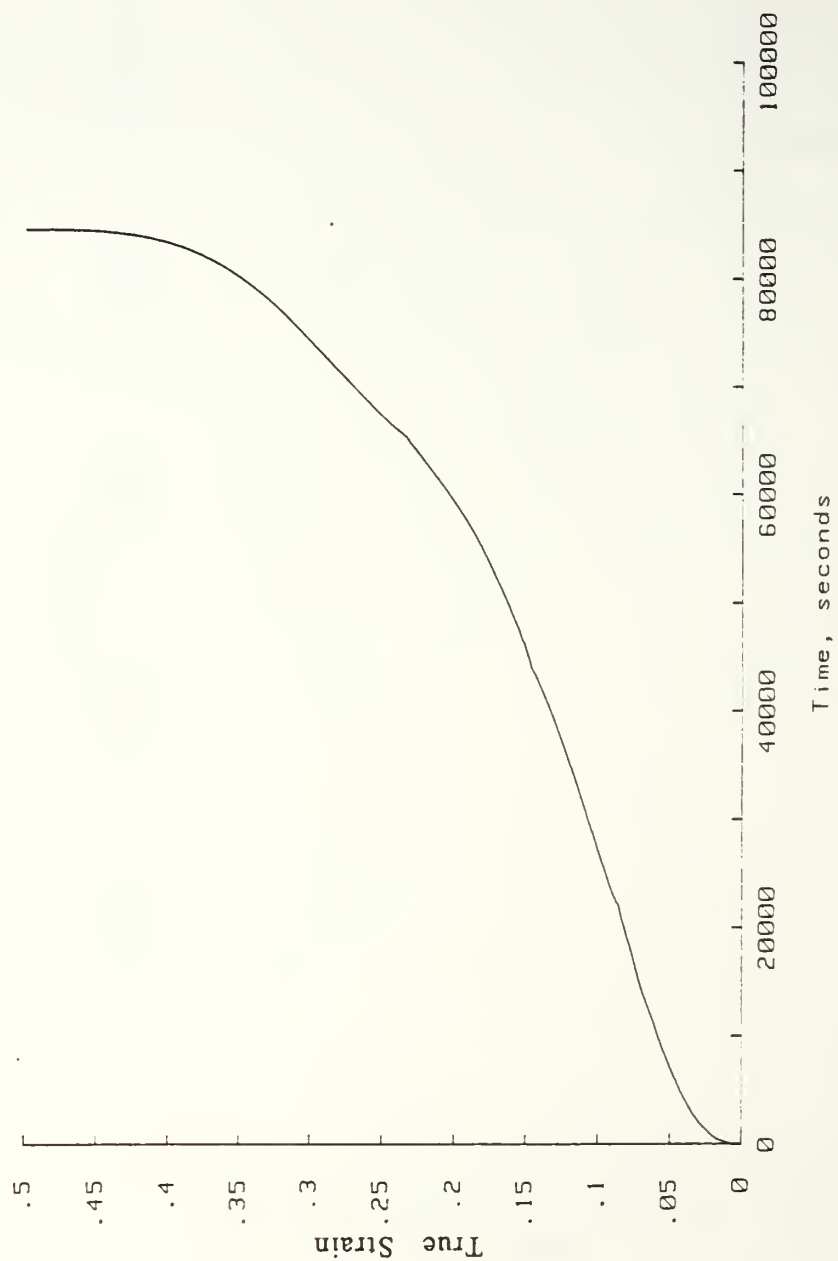


Figure 43. Creep Curve at 470-480°C for a Stress of 2.03 MPa:

$$\dot{\epsilon}_1 = 1.75 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 2.52 \times 10^{-6} \text{ sec}^{-1}$$

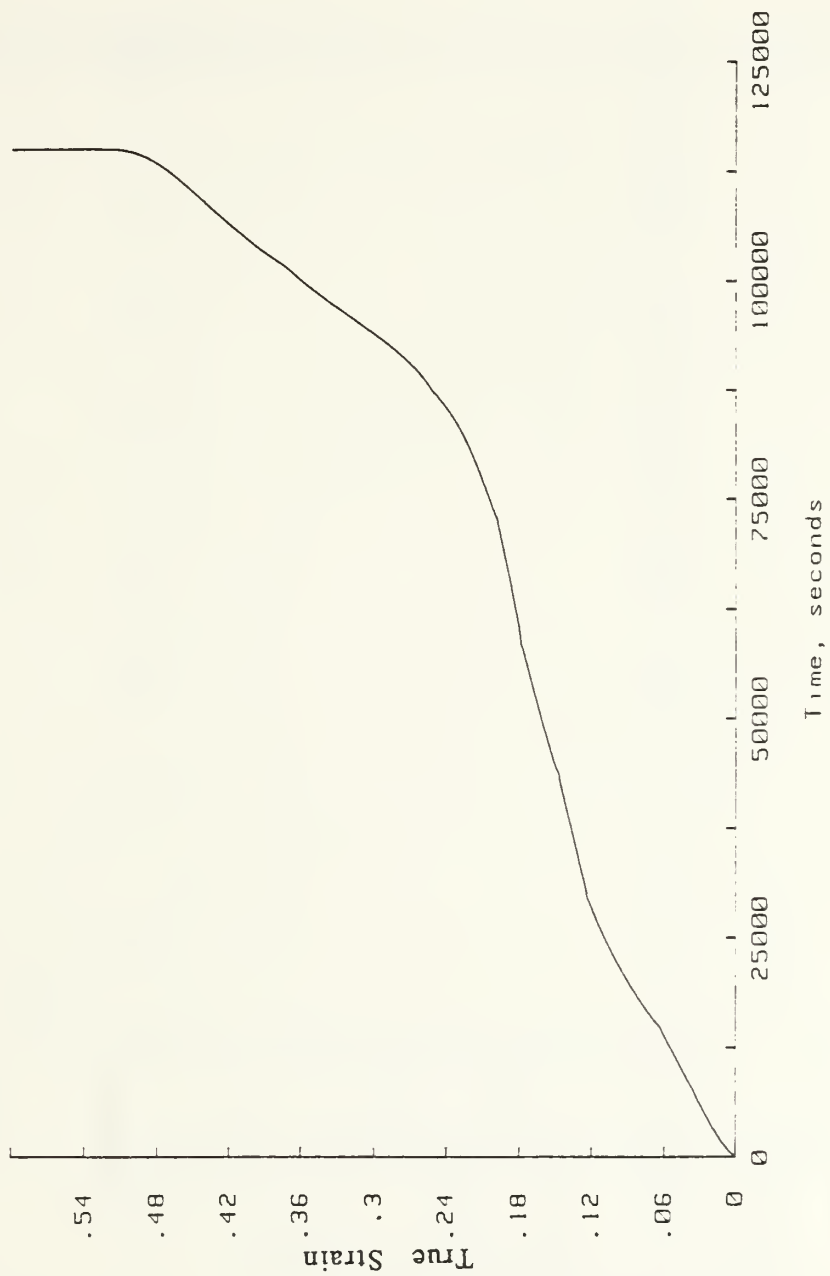


Figure 44. Creep Curve at 500-510°C for a Stress of 1.64 MPa:

$$\dot{\epsilon}_1 = 1.51 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 1.99 \times 10^{-6} \text{ sec}^{-1}$$

APPENDIX D. CREEP RATE CURVES

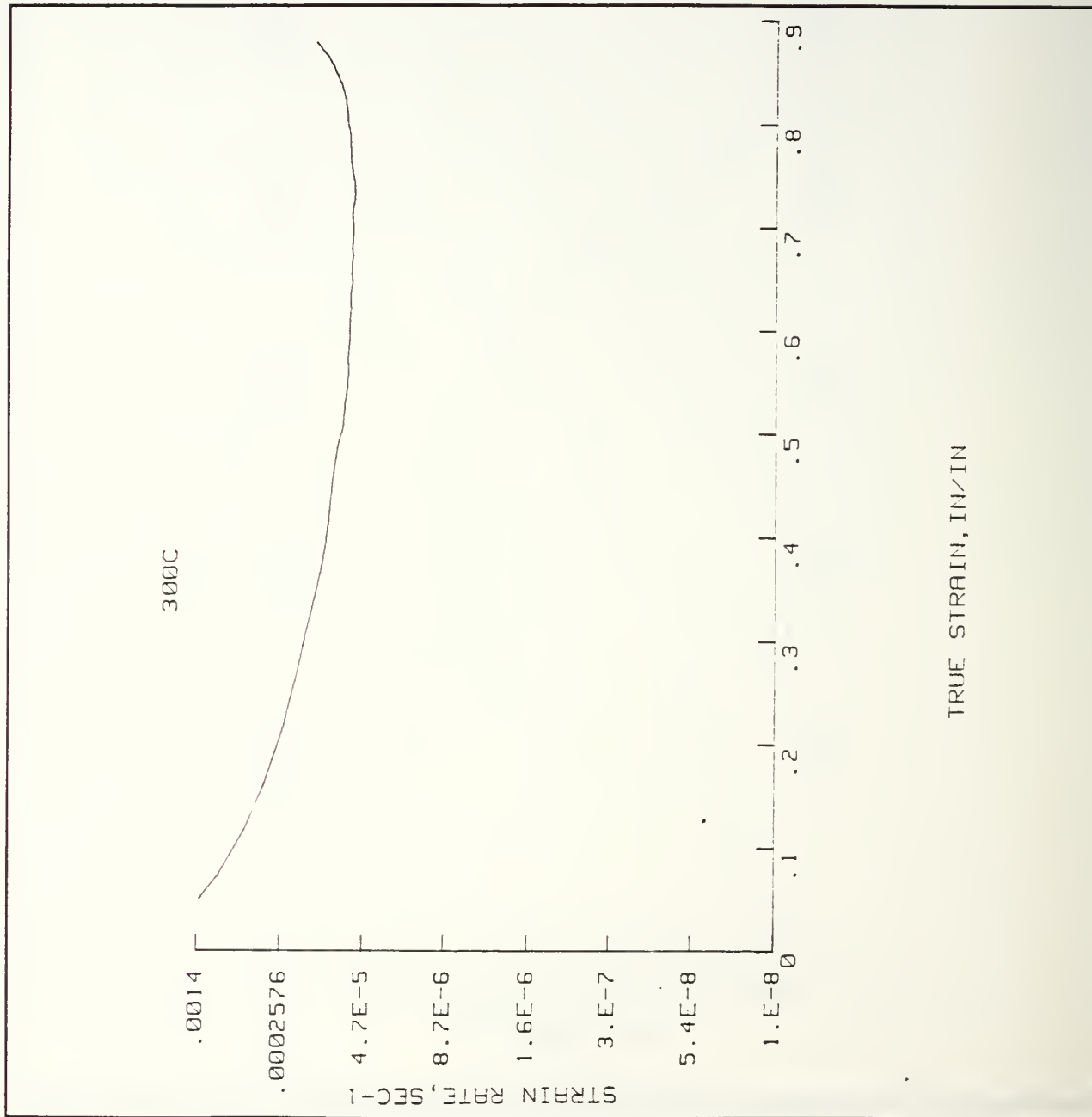


Figure 45. Creep Rate Curve at 300°C for a Stress of 21.2 MPa:

$$\dot{\epsilon}_{\min} = 6.10 \times 10^{-5} \text{ sec}^{-1}$$

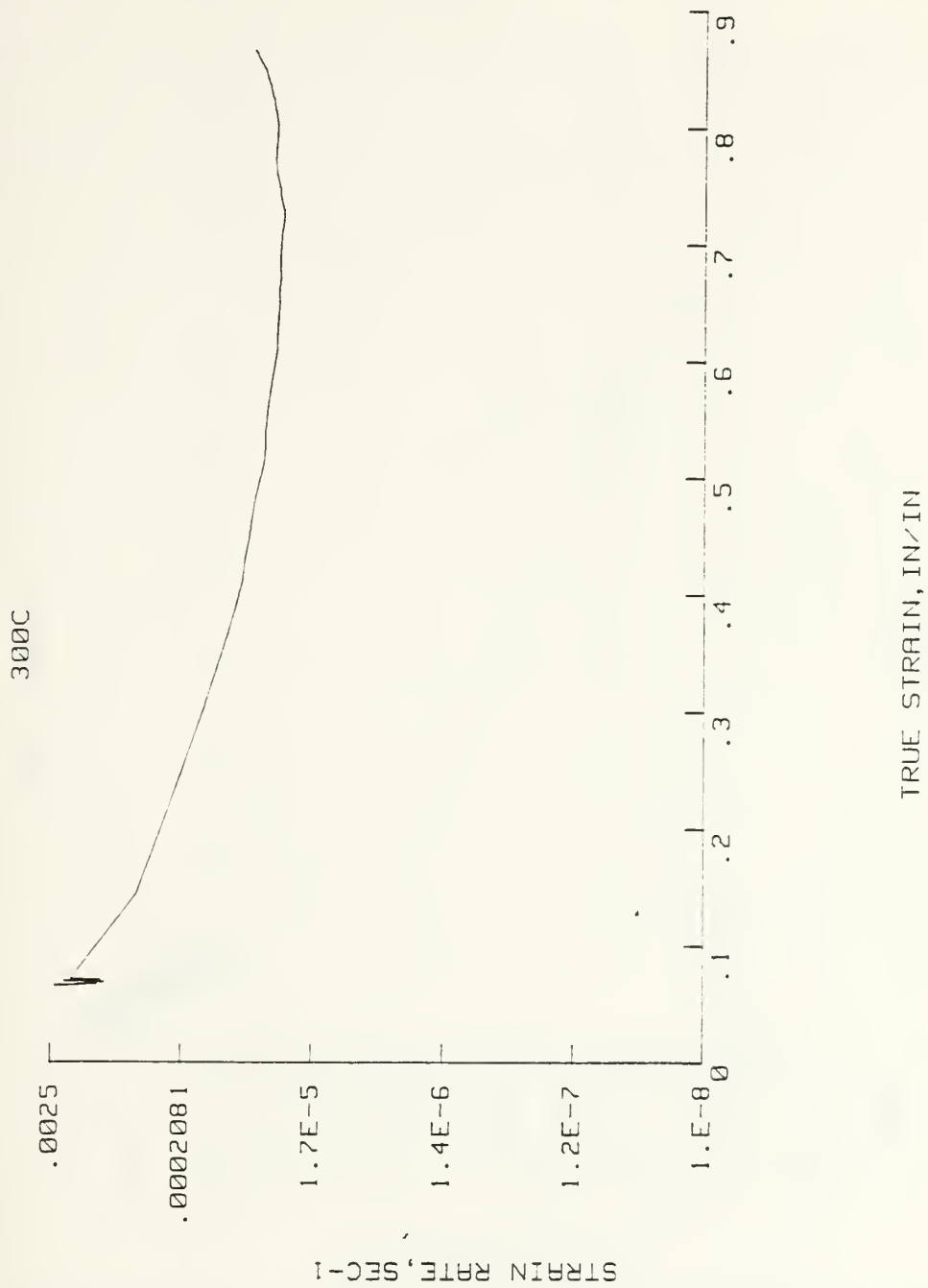


Figure 46. Creep Rate Curve at 300°C for a Stress of 19.0 MPa:

$$\dot{\epsilon}_{\min} = 3.32 \times 10^{-5} \text{ sec}^{-1}$$

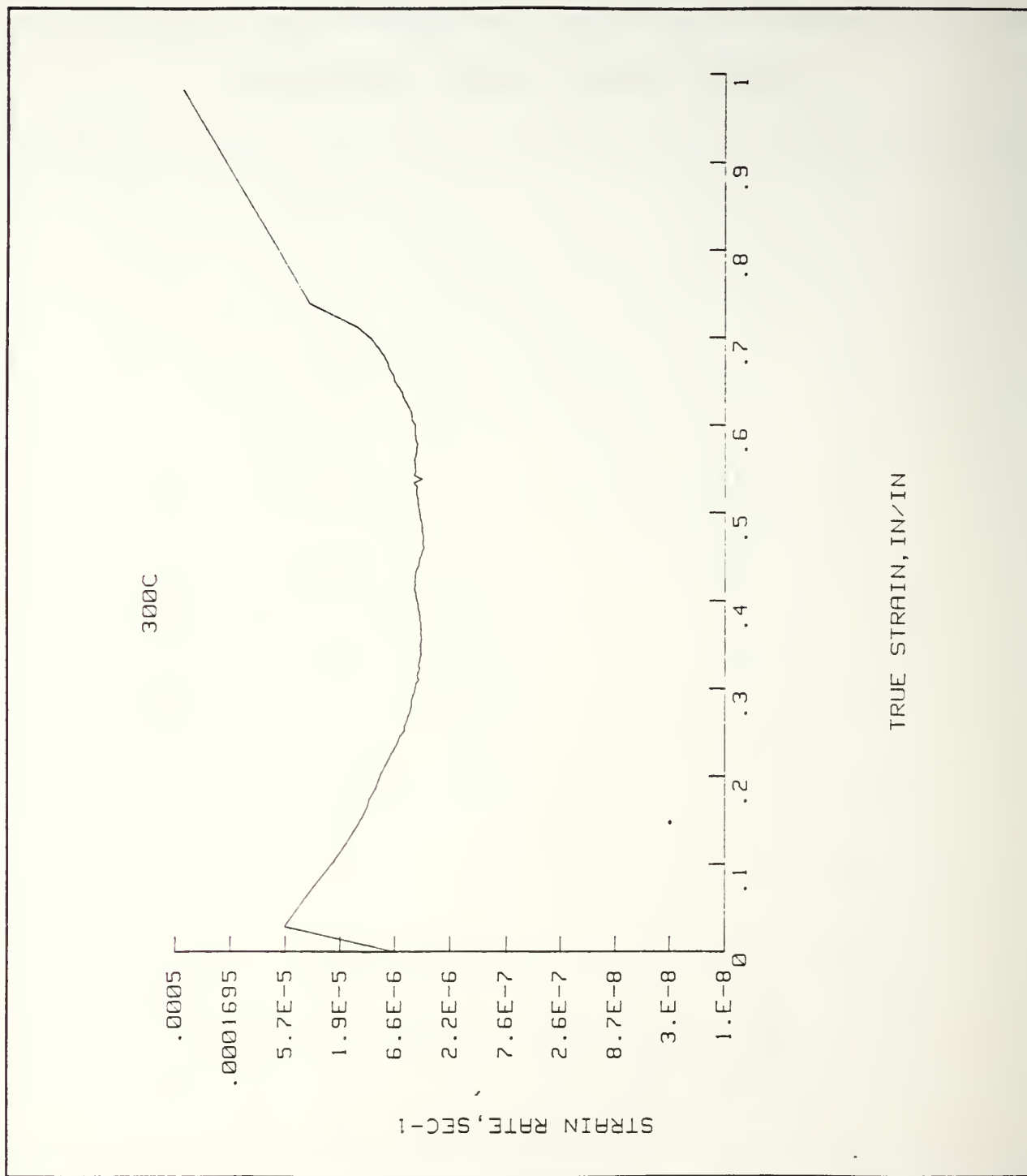


Figure 47. Creep Rate Curve at 300°C for a Stress of 13.0 MPa:

$$\dot{\epsilon}_{\min} = 3.76 \times 10^{-6} \text{ sec}^{-1}$$



Figure 48. Creep Rate Curve at 350°C for a Stress of 21.2 MPa:

$$\dot{\epsilon}_{\min} = 4.96 \times 10^{-3} \text{ sec}^{-1}$$

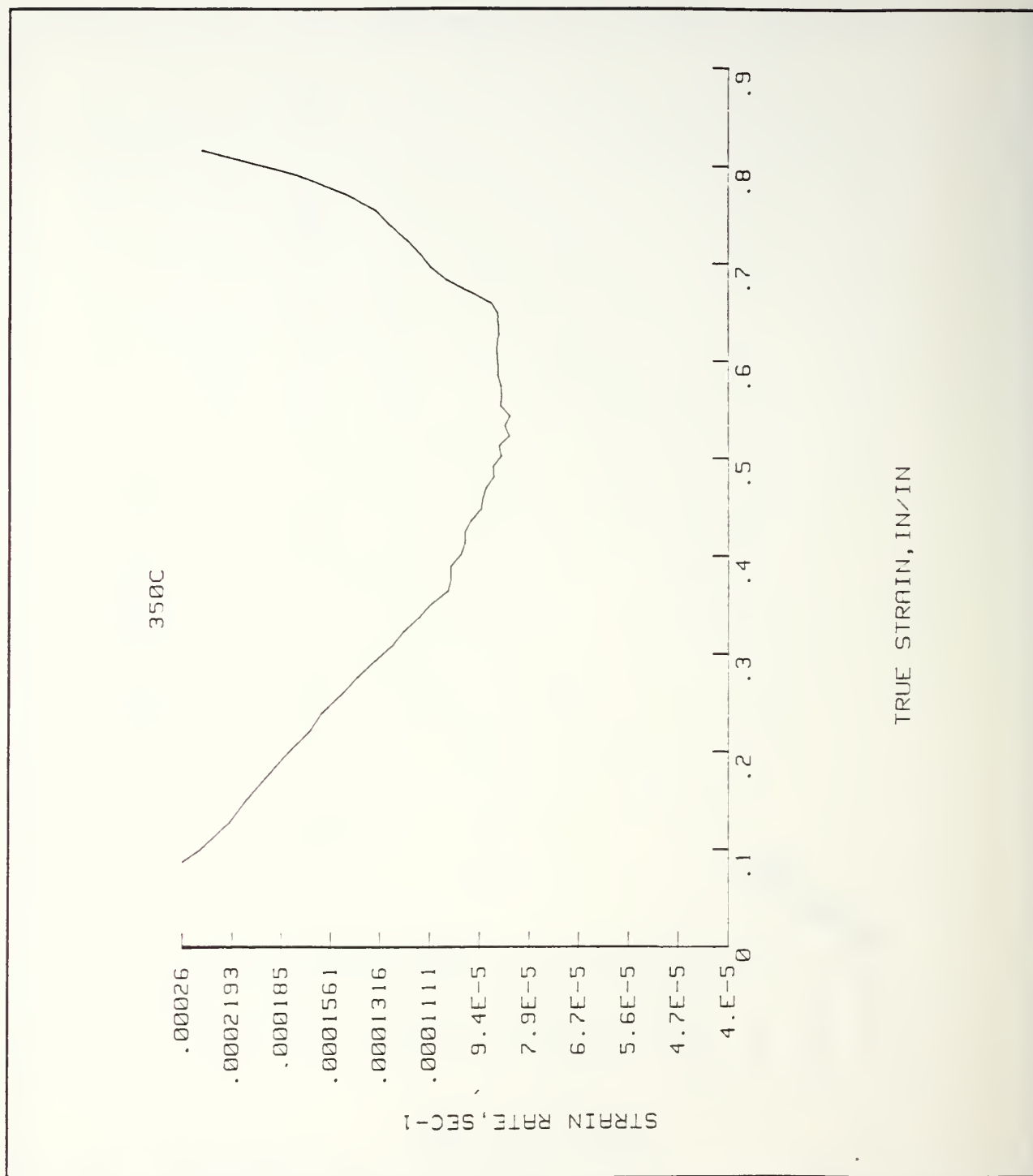


Figure 49. Creep Rate Curve at 350°C for a Stress of 12.9 MPa:

$$\dot{\epsilon}_{\min} = 8.57 \times 10^{-5} \text{ sec}^{-1}$$



Figure 50. Creep Rate Curve at 350°C for a Stress of 7.00 MPa:

$$\dot{\epsilon}_{\min} = 1.94 \times 10^{-6} \text{ sec}^{-1}$$

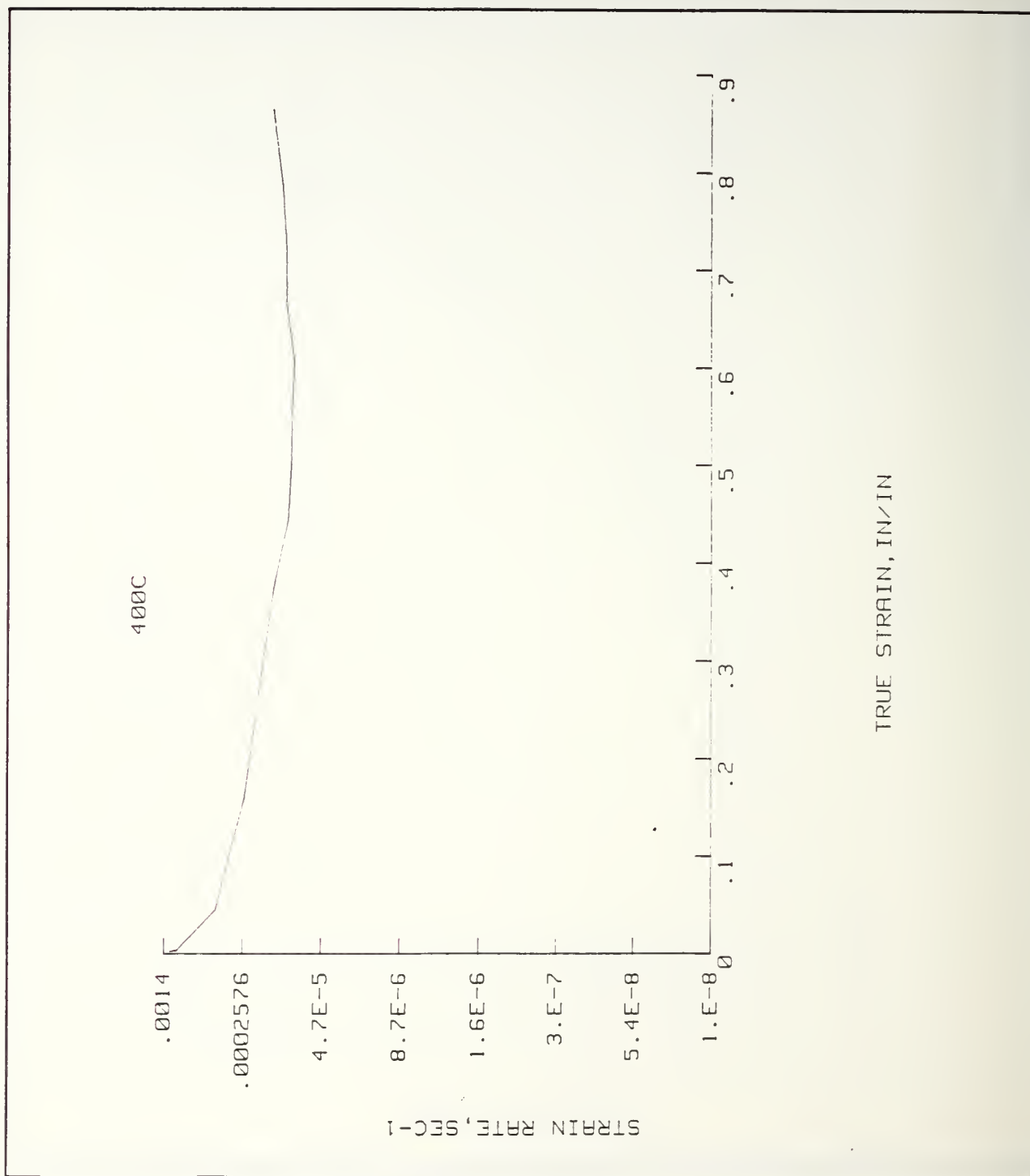


Figure 51. Creep Rate Curve at 400°C for a Stress of 7.10 MPa:

$$\dot{\epsilon}_{\min} = 9.66 \times 10^{-5} \text{ sec}^{-1}$$

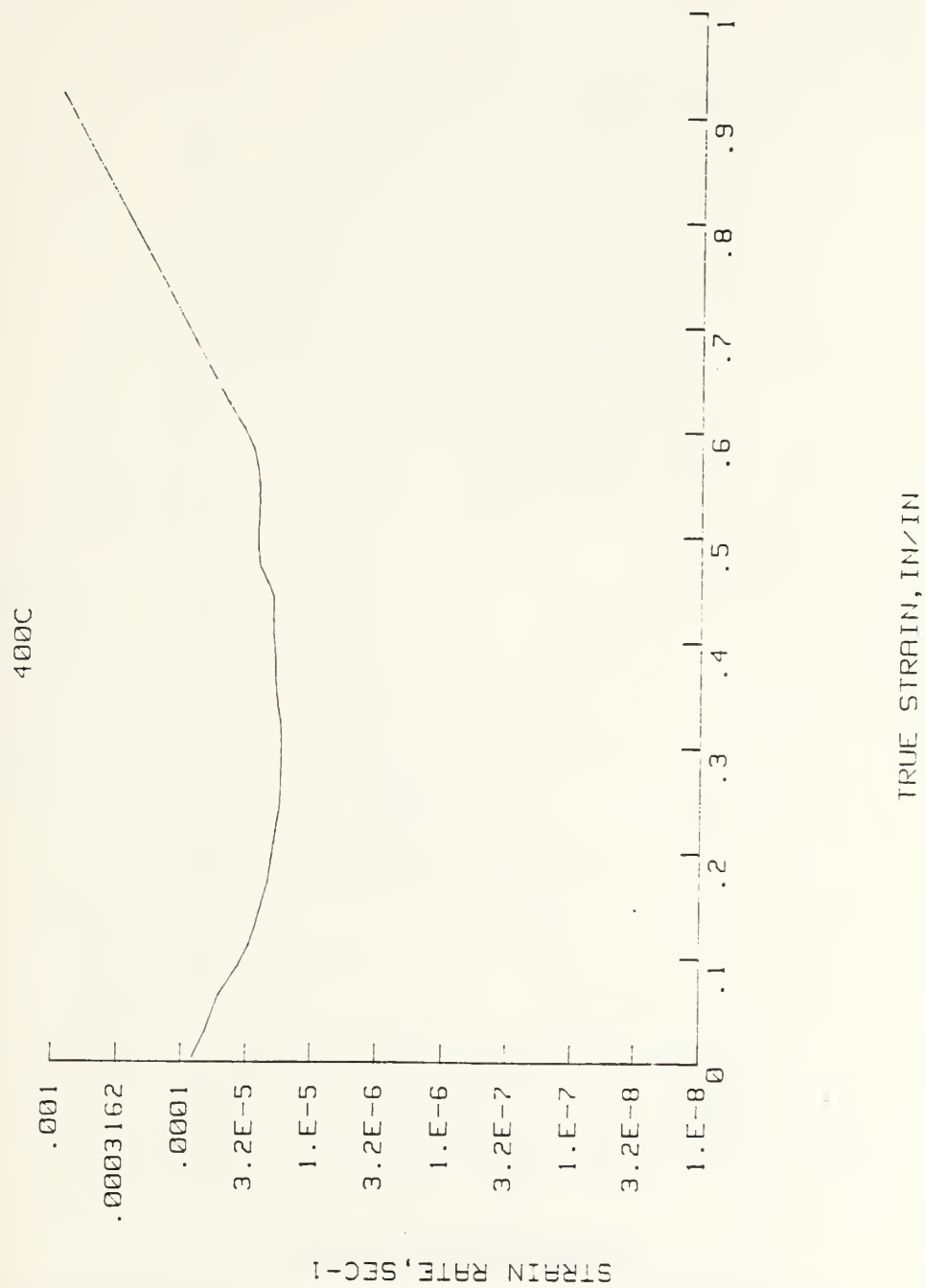


Figure 52. Creep Rate Curve at 400°C for a Stress of 5.27 MPa:

$$\dot{\epsilon}_{\min} = 1.73 \times 10^{-5} \text{ sec}^{-1}$$

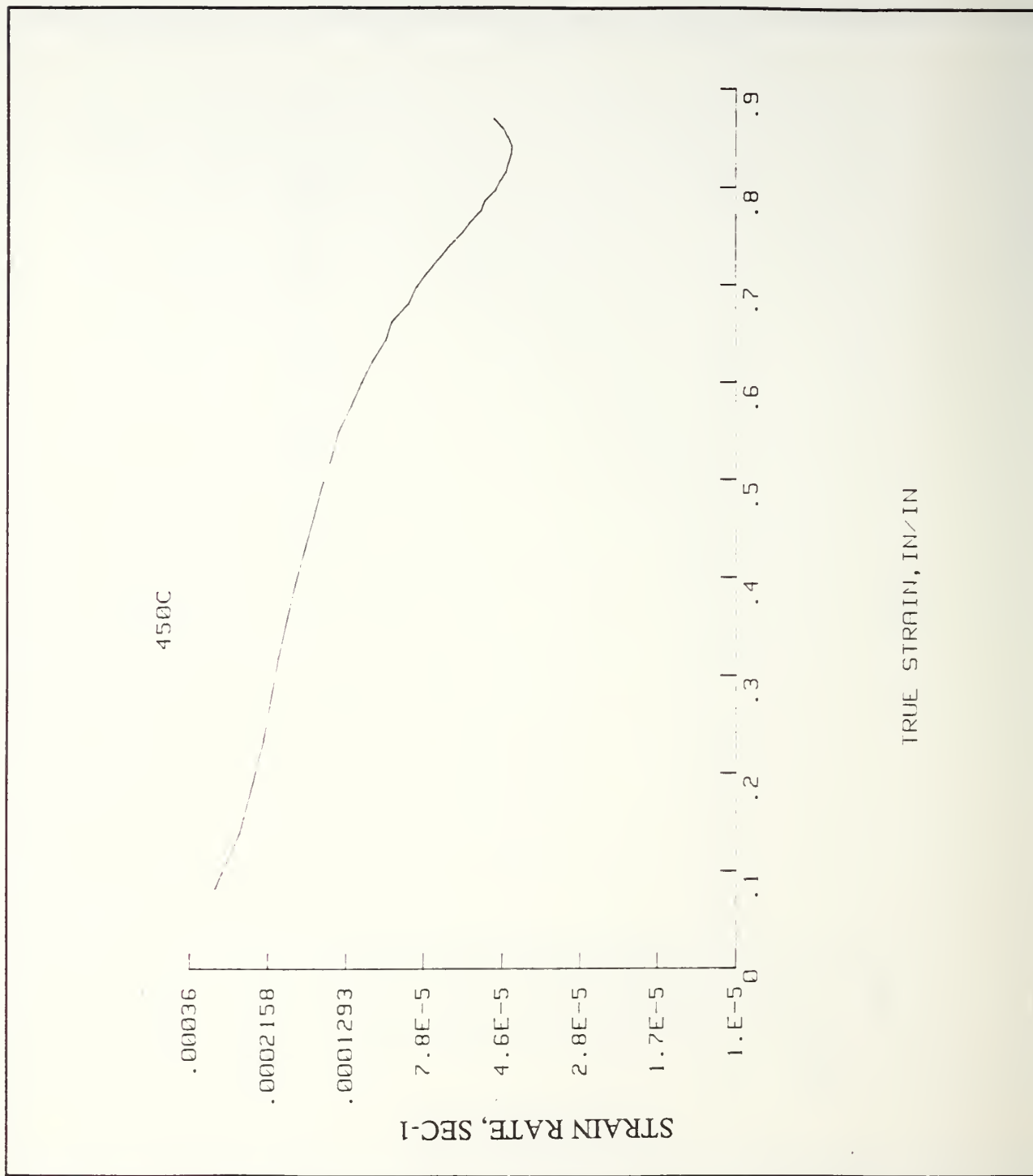


Figure 53. Creep Rate Curve at 450°C for a Stress of 2.35 MPa:

$$\dot{\epsilon}_{\min} = 4.37 \times 10^{-5} \text{ sec}^{-1}$$

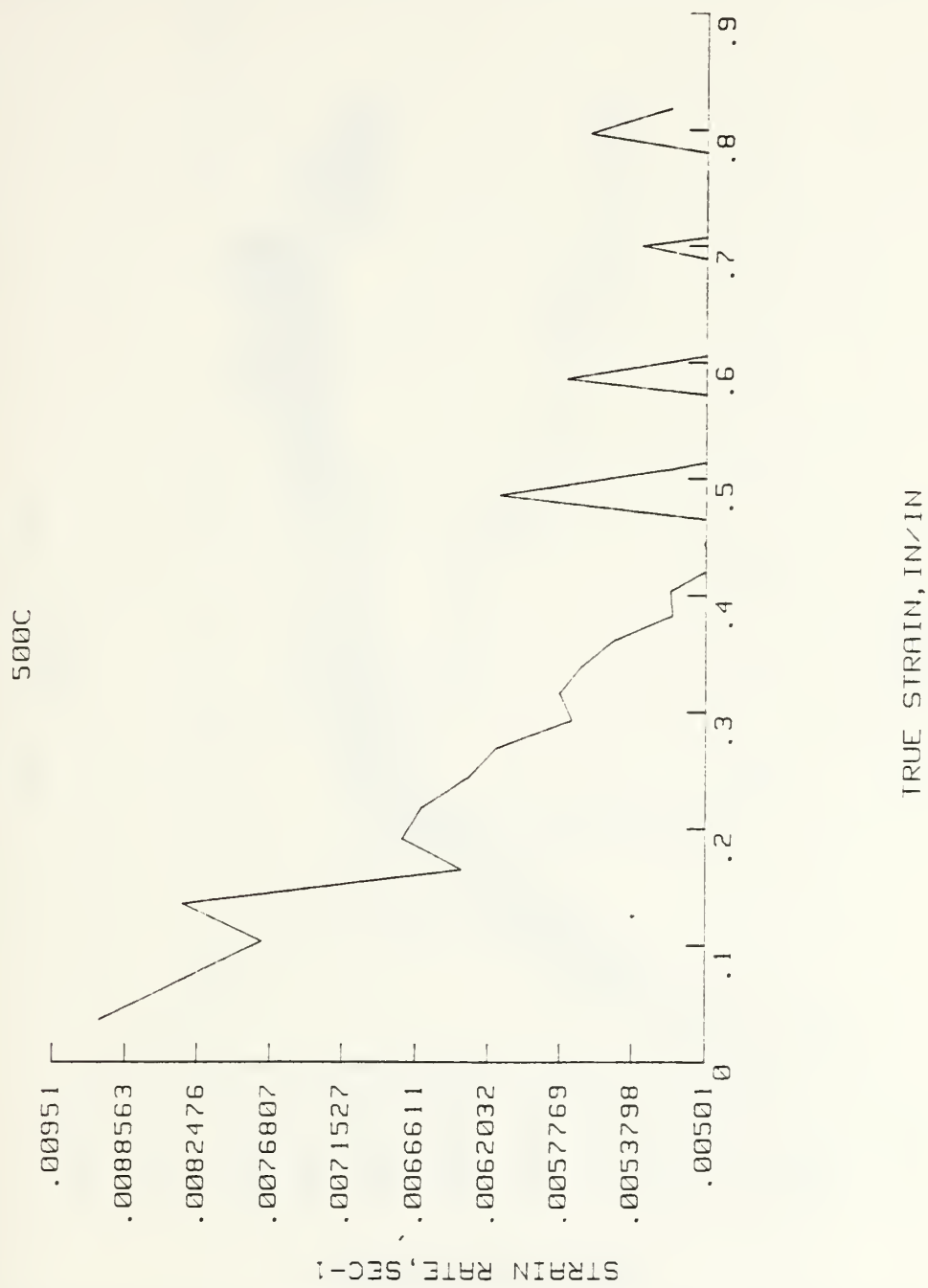


Figure 54. Creep Rate Curve at 500°C for a Stress of 5.48 MPa:

$$\dot{\epsilon}_{\min} = 4.83 \times 10^{-3} \text{ sec}^{-1}$$



Figure 55. Creep Rate Curve at 500°C for a Stress of 3.02 MPa:

$$\dot{\epsilon}_{\min} = 2.43 \times 10^{-4} \text{ sec}^{-1}$$



Figure 56. Creep Rate Curve at 500°C for a Stress of 2.25 MPa:

$$\dot{\epsilon}_{\min} = 6.36 \times 10^{-5} \text{ sec}^{-1}$$

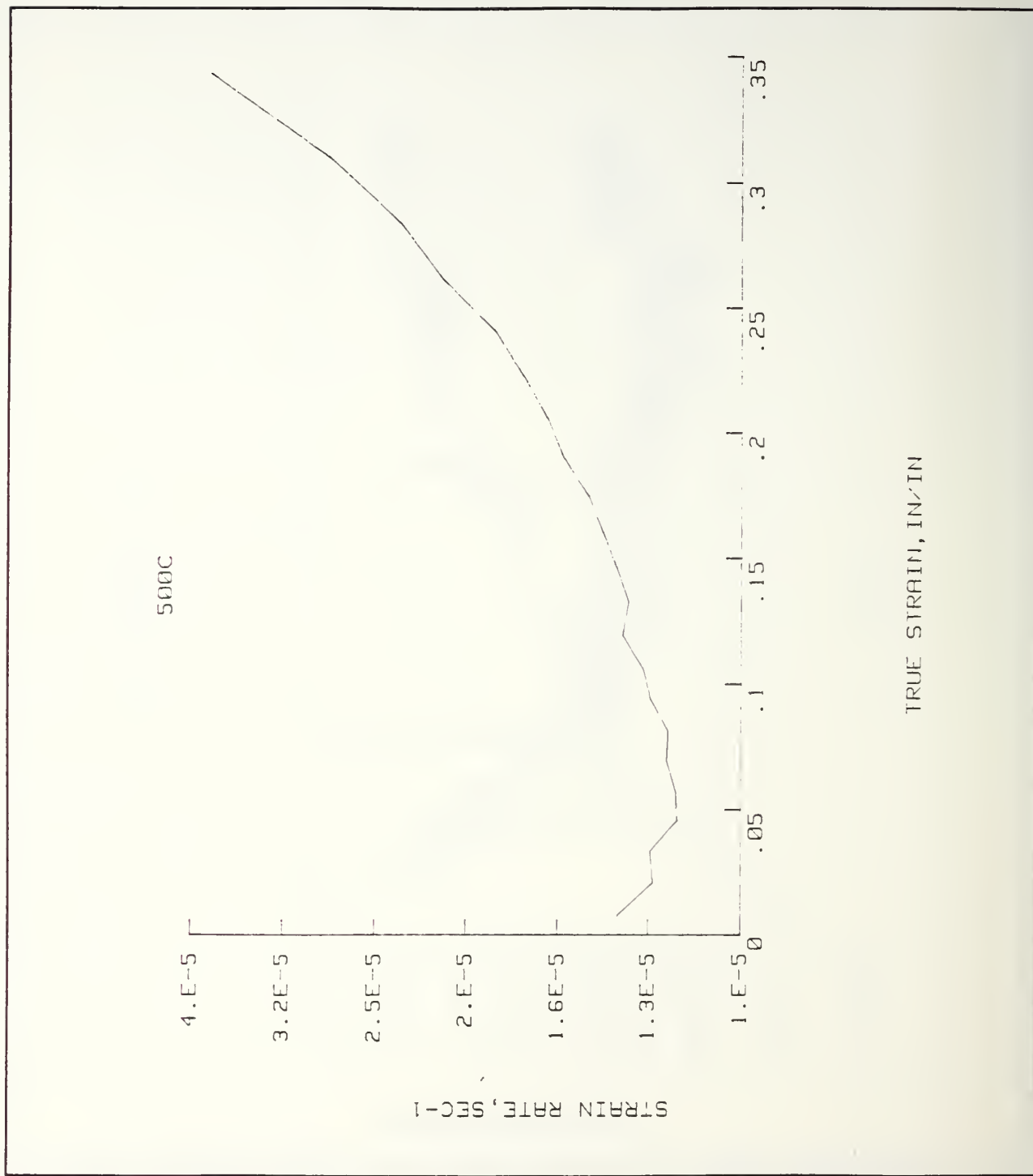


Figure 57. Creep Rate Curve at 500°C for a Stress of 1.84 MPa:

$$\dot{\epsilon}_{\min} = 1.17 \times 10^{-5} \text{ sec}^{-1}$$

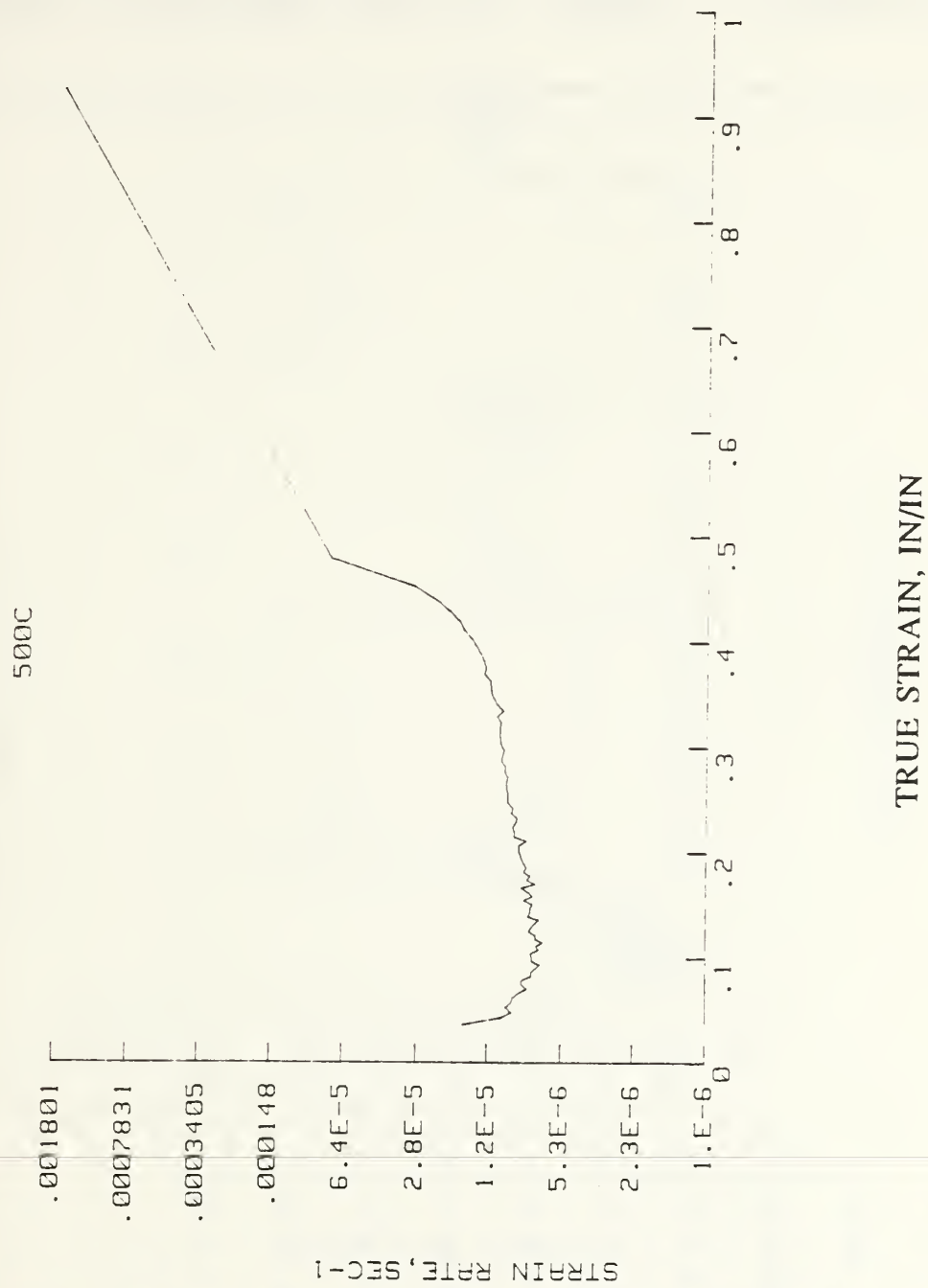


Figure 58. Creep Rate Curve at 500°C for a Stress of 1.63 MPa:

$$\dot{\epsilon}_{\min} = 6.52 \times 10^{-6} \text{ sec}^{-1}$$

APPENDIX E. TEMP. CYCLING CREEP RATE CURVES

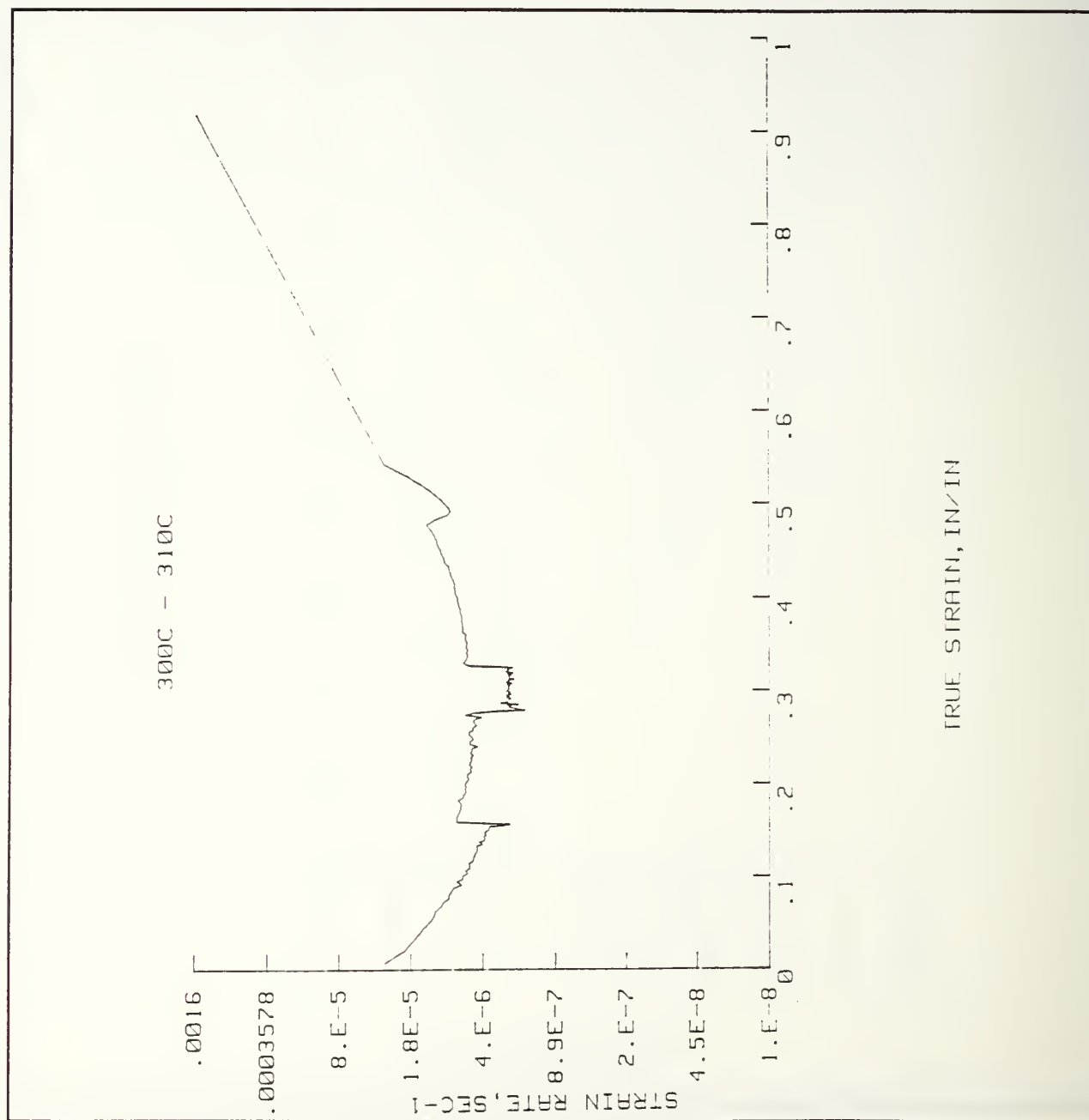


Figure 59. Creep Rate Curve at 300-310°C for a Stress of 11.9 MPa:

$$\dot{\epsilon}_1 = 2.46 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 4.92 \times 10^{-6} \text{ sec}^{-1}$$

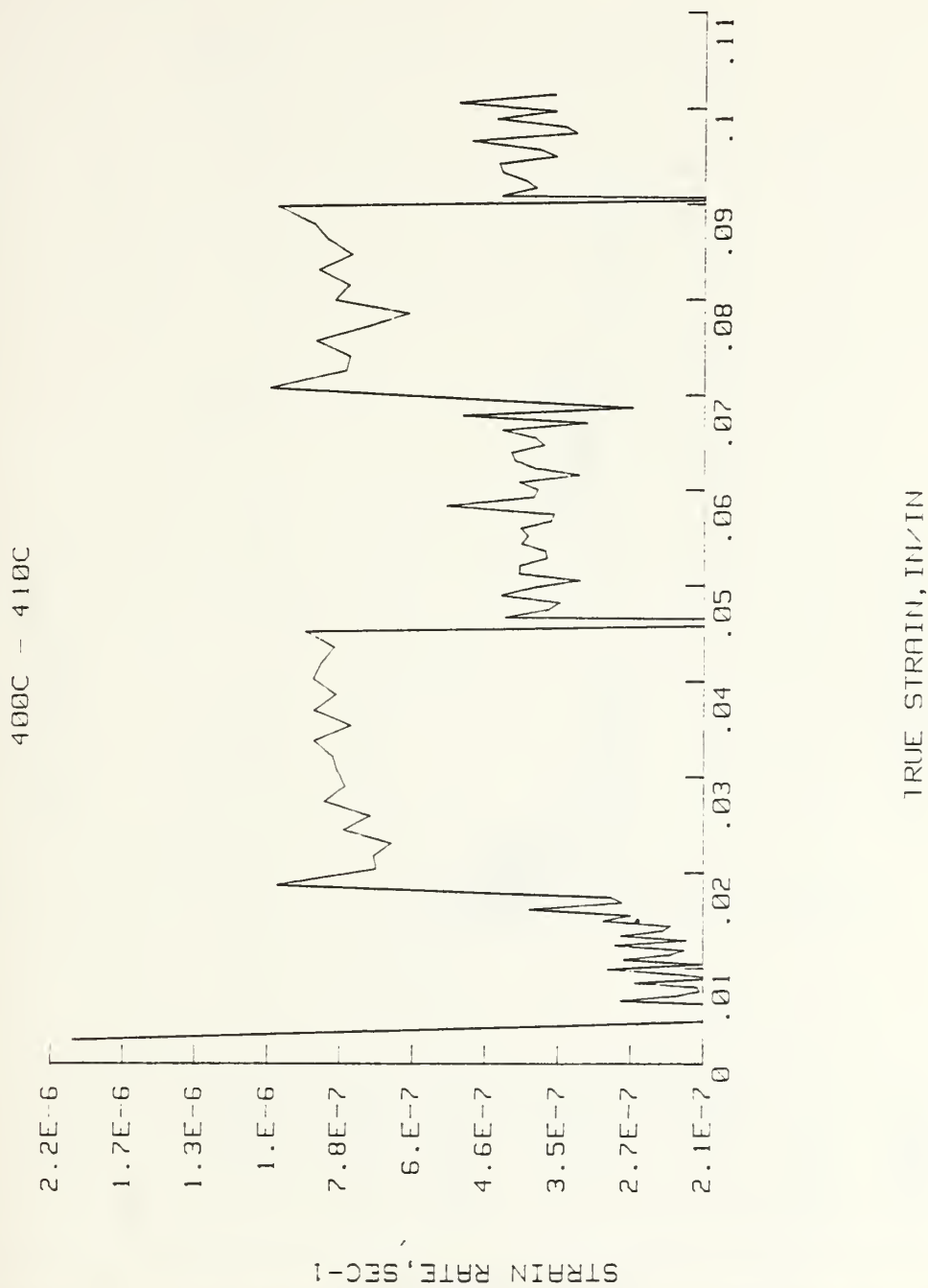


Figure 60. Creep Rate Curve at 400-410°C for a Stress of 3.03 MPa:

$$\dot{\epsilon}_1 = 4.02 \times 10^{-7} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 7.90 \times 10^{-7} \text{ sec}^{-1}$$

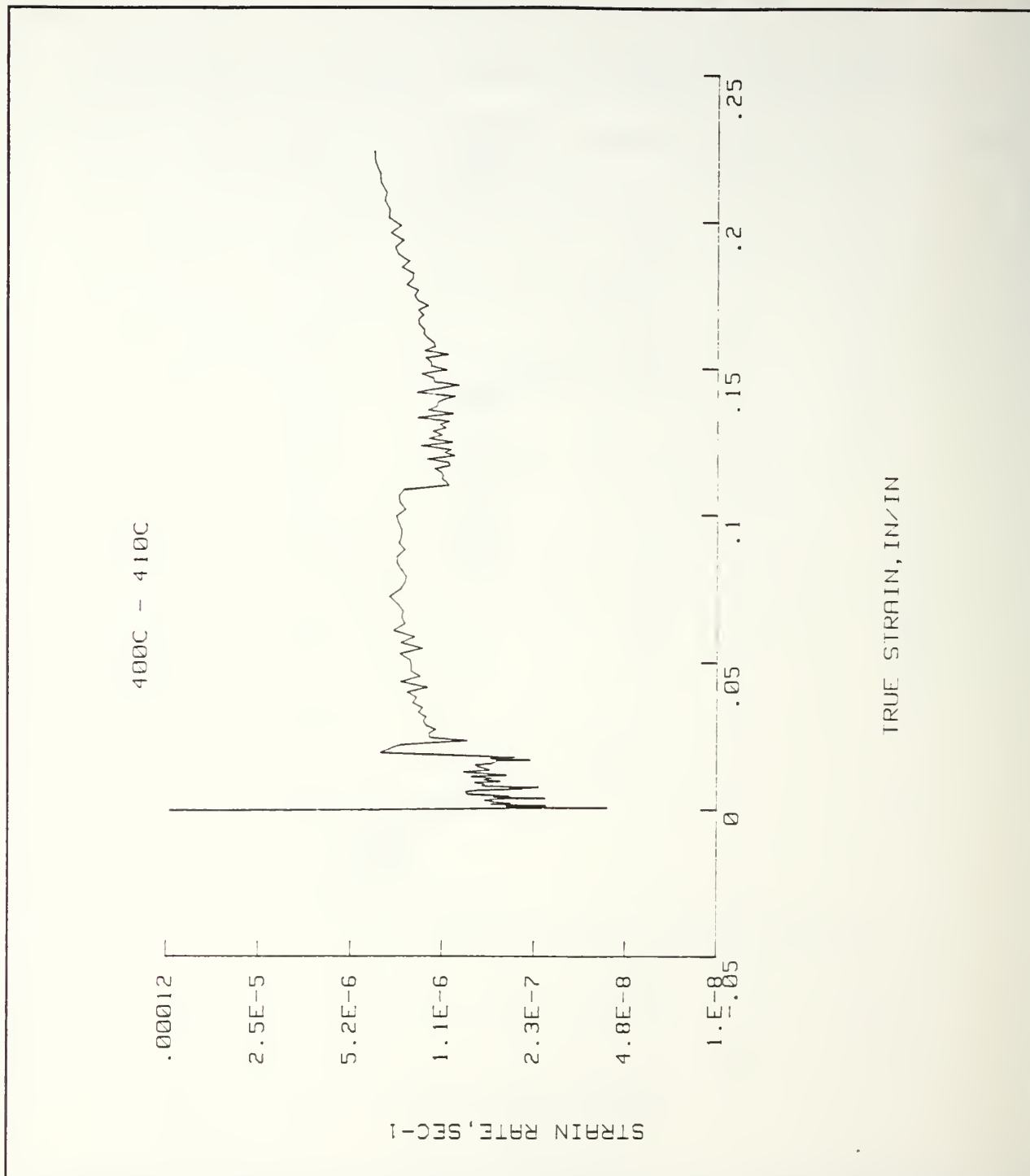


Figure 61. Creep Rate Curve at 400-410°C for a Stress of 3.03 MPa:

$$\dot{\epsilon}_1 = 1.20 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 2.21 \times 10^{-6} \text{ sec}^{-1}$$

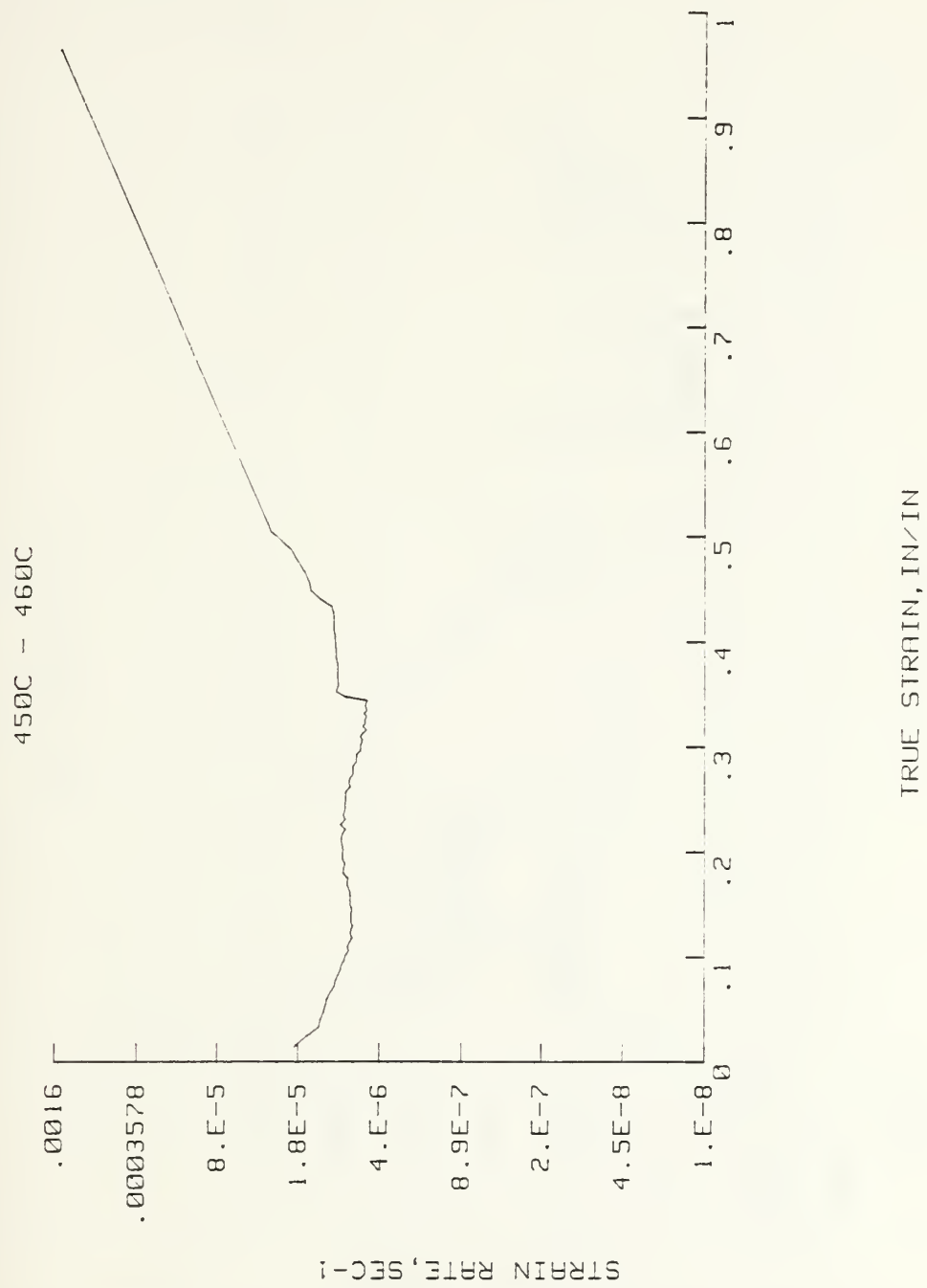


Figure 62. Creep Rate Curve at 450-460°C for a Stress of 2.46 MPa:

$$\dot{\epsilon}_1 = 8.73 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 5.19 \times 10^{-6} \text{ sec}^{-1}$$

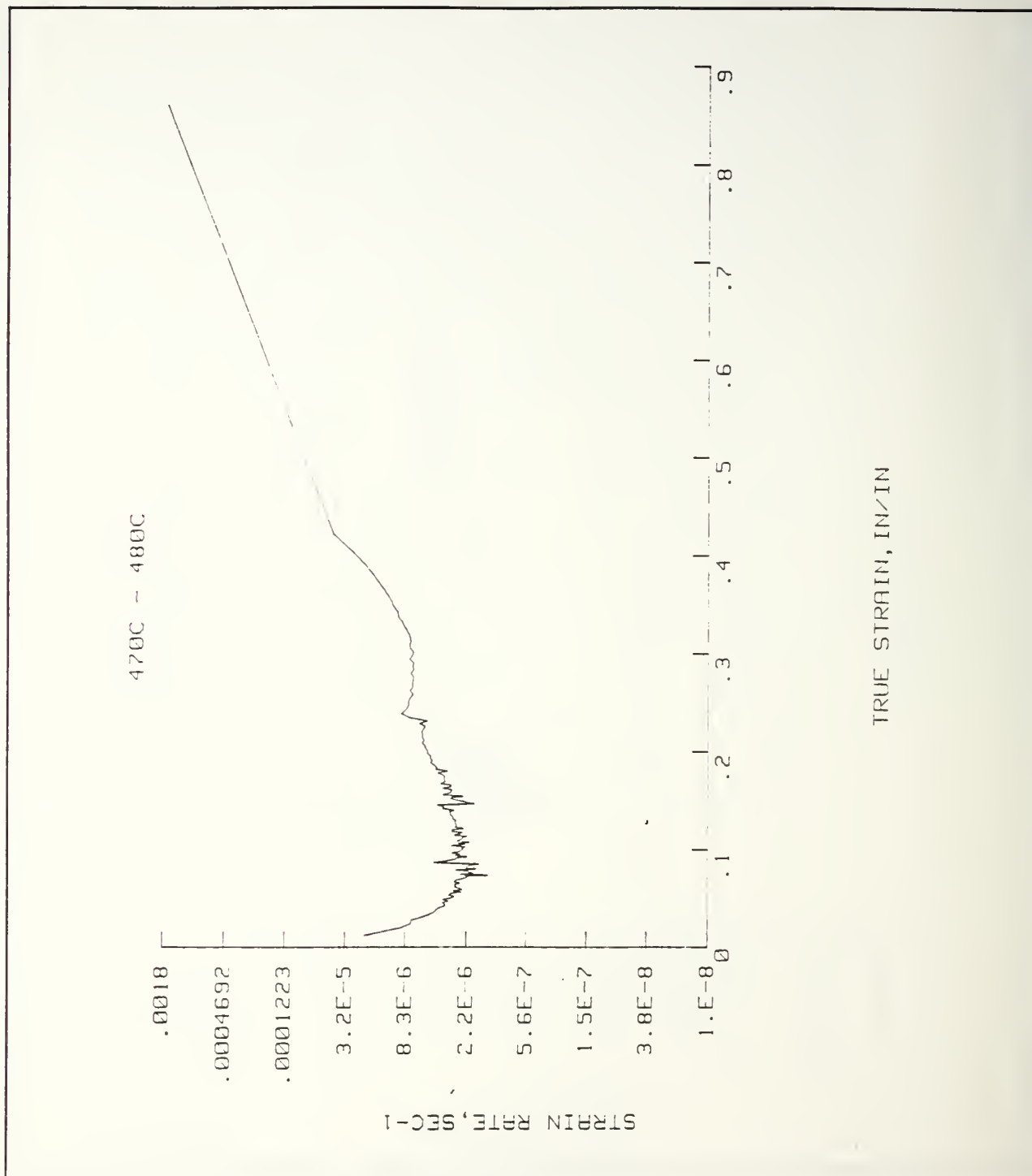


Figure 63. Creep Rate Curve at 470-480°C for a Stress of 2.03 MPa:

$$\dot{\epsilon}_1 = 2.13 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 2.52 \times 10^{-6} \text{ sec}^{-1}$$

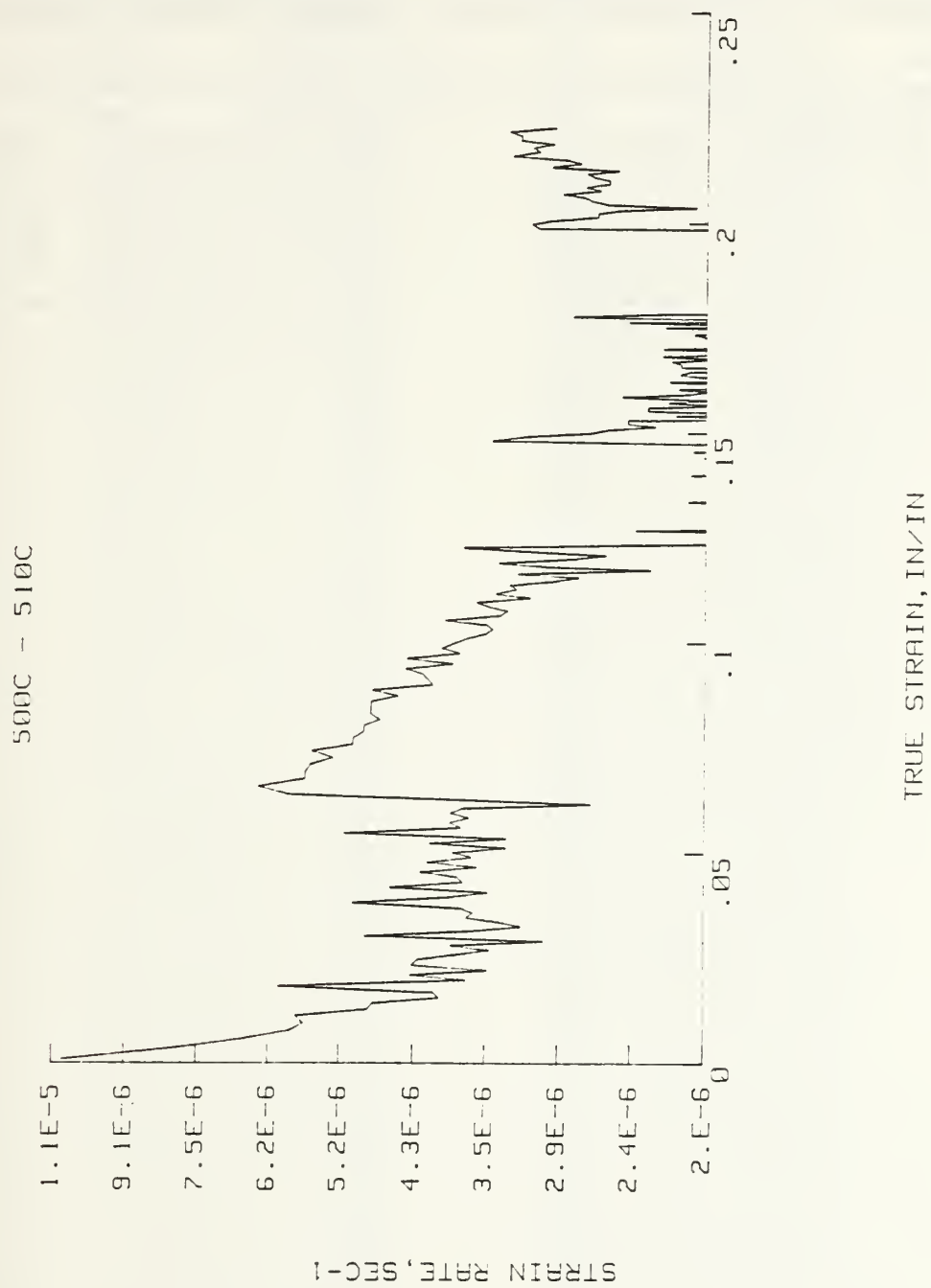


Figure 64. Creep Rate Curve at 500-510°C for a Stress of 1.64 MPa:

$$\dot{\epsilon}_1 = 1.99 \times 10^{-6} \text{ sec}^{-1} \text{ \& \; } \dot{\epsilon}_2 = 2.77 \times 10^{-6} \text{ sec}^{-1}$$

APPENDIX F. EXAMPLE DATA TABLES FROM PROGRAM

FILENAME IS TEST240					
RDG #	TRUESTRAIN	TIME, SEC	RDG #	TRUESTRAIN	TIME, SEC
2	+7.353E-03	+5.010E+00	4	+1.550E-02	+1.501E+01
6	+2.211E-02	+2.501E+01	8	+2.837E-02	+3.501E+01
10	+3.376E-02	+4.501E+01	12	+3.920E-02	+5.502E+01
14	+4.440E-02	+6.502E+01	16	+4.904E-02	+7.502E+01
18	+5.407E-02	+8.502E+01	20	+5.853E-02	+9.502E+01
22	+6.328E-02	+1.050E+02	24	+6.753E-02	+1.150E+02
26	+7.199E-02	+1.250E+02	28	+7.607E-02	+1.350E+02
30	+8.031E-02	+1.450E+02	32	+8.416E-02	+1.550E+02
34	+8.805E-02	+1.651E+02	36	+9.170E-02	+1.750E+02
38	+9.531E-02	+1.850E+02	40	+9.878E-02	+1.950E+02
42	+1.023E-01	+2.051E+02	44	+1.056E-01	+2.151E+02
46	+1.089E-01	+2.251E+02	48	+1.121E-01	+2.351E+02
50	+1.153E-01	+2.451E+02	52	+1.184E-01	+2.551E+02
54	+1.215E-01	+2.651E+02	56	+1.244E-01	+2.751E+02
58	+1.274E-01	+2.851E+02	60	+1.303E-01	+2.951E+02
62	+1.331E-01	+3.051E+02	64	+1.360E-01	+3.151E+02
66	+1.388E-01	+3.251E+02	68	+1.417E-01	+3.351E+02
70	+1.445E-01	+3.451E+02	72	+1.474E-01	+3.551E+02
74	+1.502E-01	+3.651E+02	76	+1.529E-01	+3.751E+02
78	+1.558E-01	+3.851E+02	80	+1.585E-01	+3.951E+02
82	+1.613E-01	+4.051E+02	84	+1.640E-01	+4.151E+02
86	+1.668E-01	+4.251E+02	88	+1.695E-01	+4.351E+02
90	+1.723E-01	+4.451E+02	92	+1.750E-01	+4.551E+02
94	+1.777E-01	+4.651E+02	96	+1.804E-01	+4.751E+02
98	+1.831E-01	+4.851E+02	100	+1.859E-01	+4.951E+02
102	+1.886E-01	+5.051E+02	104	+1.913E-01	+5.151E+02
106	+1.940E-01	+5.251E+02	108	+1.968E-01	+5.351E+02
110	+1.996E-01	+5.451E+02	112	+2.023E-01	+5.551E+02
114	+2.051E-01	+5.651E+02	116	+2.078E-01	+5.751E+02
118	+2.105E-01	+5.851E+02	120	+2.133E-01	+5.951E+02
122	+2.159E-01	+6.051E+02	124	+2.187E-01	+6.151E+02
126	+2.213E-01	+6.251E+02	128	+2.240E-01	+6.351E+02
130	+2.268E-01	+6.451E+02	132	+2.294E-01	+6.551E+02
134	+2.322E-01	+6.651E+02	136	+2.348E-01	+6.751E+02
138	+2.376E-01	+6.851E+02	140	+2.401E-01	+6.951E+02
142	+2.429E-01	+7.052E+02	144	+2.454E-01	+7.151E+02
146	+2.482E-01	+7.251E+02	148	+2.506E-01	+7.352E+02
150	+2.533E-01	+7.451E+02	152	+2.558E-01	+7.552E+02
154	+2.585E-01	+7.652E+02	156	+2.608E-01	+7.752E+02
158	+2.634E-01	+7.852E+02	160	+2.657E-01	+7.952E+02
162	+2.684E-01	+8.052E+02	164	+2.706E-01	+8.152E+02

Figure 65. Creep Data Table

166	+2.732E-01	+8.252E+02	168	+2.754E-01	+8.352E+02
170	+2.780E-01	+8.452E+02	172	+2.803E-01	+8.552E+02
174	+2.828E-01	+8.652E+02	176	+2.850E-01	+8.752E+02
178	+2.875E-01	+8.852E+02	180	+2.897E-01	+8.952E+02
182	+2.922E-01	+9.052E+02	184	+2.944E-01	+9.152E+02
186	+2.970E-01	+9.252E+02	188	+2.992E-01	+9.352E+02
190	+3.018E-01	+9.452E+02	192	+3.040E-01	+9.552E+02
194	+3.064E-01	+9.652E+02	196	+3.087E-01	+9.752E+02
198	+3.112E-01	+9.852E+02	200	+3.134E-01	+9.952E+02
202	+3.159E-01	+1.005E+03	204	+3.181E-01	+1.015E+03
206	+3.206E-01	+1.025E+03	208	+3.229E-01	+1.035E+03
210	+3.254E-01	+1.045E+03	212	+3.276E-01	+1.055E+03
214	+3.301E-01	+1.065E+03	216	+3.323E-01	+1.075E+03
218	+3.348E-01	+1.085E+03	220	+3.370E-01	+1.095E+03
222	+3.395E-01	+1.105E+03	224	+3.417E-01	+1.115E+03
226	+3.441E-01	+1.125E+03	228	+3.463E-01	+1.135E+03
230	+3.487E-01	+1.145E+03	232	+3.508E-01	+1.155E+03
234	+3.533E-01	+1.165E+03	236	+3.554E-01	+1.175E+03
238	+3.578E-01	+1.185E+03	240	+3.602E-01	+1.195E+03
242	+3.633E-01	+1.205E+03	244	+3.659E-01	+1.215E+03
246	+3.688E-01	+1.225E+03	248	+3.714E-01	+1.235E+03
250	+3.744E-01	+1.245E+03	252	+3.769E-01	+1.255E+03
254	+3.798E-01	+1.265E+03	256	+3.824E-01	+1.275E+03
258	+3.853E-01	+1.285E+03	260	+3.878E-01	+1.295E+03
262	+3.906E-01	+1.305E+03	264	+3.932E-01	+1.315E+03
266	+3.960E-01	+1.325E+03	268	+3.986E-01	+1.335E+03
270	+4.015E-01	+1.345E+03	272	+4.042E-01	+1.355E+03
274	+4.072E-01	+1.365E+03	276	+4.100E-01	+1.375E+03
278	+4.131E-01	+1.385E+03	280	+4.161E-01	+1.395E+03
282	+4.192E-01	+1.405E+03	284	+4.223E-01	+1.415E+03
286	+4.256E-01	+1.425E+03	288	+4.287E-01	+1.435E+03
290	+4.321E-01	+1.445E+03	292	+4.353E-01	+1.455E+03
294	+4.387E-01	+1.465E+03	296	+4.420E-01	+1.475E+03
298	+4.455E-01	+1.485E+03	300	+4.487E-01	+1.495E+03
302	+4.523E-01	+1.505E+03	304	+4.555E-01	+1.515E+03
306	+4.589E-01	+1.525E+03	308	+4.621E-01	+1.535E+03
310	+4.655E-01	+1.545E+03	312	+4.686E-01	+1.555E+03
314	+4.720E-01	+1.565E+03	316	+4.751E-01	+1.575E+03
318	+4.786E-01	+1.585E+03	320	+4.816E-01	+1.595E+03
322	+4.850E-01	+1.605E+03	324	+4.880E-01	+1.615E+03
326	+4.913E-01	+1.625E+03	328	+4.944E-01	+1.635E+03
330	+4.977E-01	+1.645E+03	332	+5.009E-01	+1.655E+03
334	+5.043E-01	+1.665E+03	336	+5.075E-01	+1.675E+03
338	+5.111E-01	+1.685E+03	340	+5.145E-01	+1.695E+03

Figure 65. Creep Data Table (Continued)

FILENAME IS TEST240		
INTERVAL	AUG STRAIN	STRAIN RATE
2- 12	+2.328E-02	+6.368E-04
12- 22	+5.124E-02	+4.914E-04
22- 32	+7.372E-02	+4.176E-04
32- 42	+9.324E-02	+3.631E-04
42- 52	+1.104E-01	+3.216E-04
52- 62	+1.257E-01	+2.935E-04
62- 72	+1.402E-01	+2.857E-04
72- 82	+1.544E-01	+2.793E-04
82- 92	+1.682E-01	+2.728E-04
92- 102	+1.818E-01	+2.716E-04
102- 112	+1.954E-01	+2.745E-04
112- 122	+2.091E-01	+2.730E-04
122- 132	+2.227E-01	+2.686E-04
132- 142	+2.361E-01	+2.706E-04
142- 152	+2.494E-01	+2.575E-04
152- 162	+2.621E-01	+2.514E-04
162- 172	+2.743E-01	+2.379E-04
172- 182	+2.862E-01	+2.390E-04
182- 192	+2.981E-01	+2.349E-04
192- 202	+3.099E-01	+2.394E-04
202- 212	+3.218E-01	+2.336E-04
212- 222	+3.335E-01	+2.368E-04
222- 232	+3.452E-01	+2.277E-04
232- 242	+3.571E-01	+2.483E-04
242- 252	+3.701E-01	+2.731E-04
252- 262	+3.838E-01	+2.735E-04
262- 272	+3.974E-01	+2.722E-04
272- 282	+4.117E-01	+3.004E-04
282- 292	+4.273E-01	+3.213E-04
292- 302	+4.438E-01	+3.399E-04
302- 312	+4.605E-01	+3.260E-04
312- 322	+4.768E-01	+3.278E-04
322- 332	+4.929E-01	+3.176E-04
332- 342	+5.095E-01	+3.460E-04
342- 352	+5.278E-01	+3.857E-04
352- 362	+5.480E-01	+4.196E-04
362- 372	+5.695E-01	+4.424E-04
372- 382	+5.928E-01	+4.877E-04
382- 392	+6.178E-01	+5.140E-04
392- 402	+6.465E-01	+6.323E-04
402- 412	+6.832E-01	+8.361E-04
412- 422	+9.756E-01	+1.086E-02
422- 432	+1.247E+00	+1.149E-06

Figure 66. Creep Rate Data Table

APPENDIX G. COMPUTER PROGRAMS FOR CREEP DATA

```
100 READ A,  N,  X1,  L1
110 FOR I= 1 TO N
120 READ X,  Y
130 S = Y/A
140 C = (10*L1)/(X1)
150 E = (X*C)/5
160 S1 = S*(1+E)
170 E1 = LOG(1+E)
180 PRINT TAB(0):X ;TAB(08):Y ;TAB(16):S ;TAB(32):E ;TAB(43):S1;TAB(57):E1
190 NEXT I
200 DATA .01642 , 17 , 314.68 , .721
210 DATA 0 , 7
220 DATA 5 , 7.4
230 DATA 10 , 7.35
240 DATA 15 , 7.25
250 DATA 20 , 7.2
255 DATA 44 , 6.5
260 DATA 68 , 5.9
270 DATA 92 , 5.3
280 DATA 116 , 4.8
290 DATA 140 , 4.3
300 DATA 164 , 3.9
310 DATA 188 , 3.55
320 DATA 212 , 3.3
330 DATA 236 , 2.9
340 DATA 260 , 2.425
350 DATA 284 , 1.6
360 DATA 308 , 0
```

Figure 67. Computer Program to Reduce Stress-Strain Data From Load-Time Data


```

10  | Program for running two creep machines
15  | Written 10-06-88 Tom Kellogg
20  | Revised 10-06-89 LT EARL F. GOODSON, SR.
25  | Stored as DT_CREPT
30  OUTPUT 709:'SI'
35  DIM On_off(2),Units(2){101
40  DIM Strain_1(5000),Strain_2(5000),Tyme_1(5000),Tyme_2(5000)
45  DIM T_0(2),T_e(2),T_i(2),Rdg(2)
50  Nr_pts=5000
55  GOTO 1
60  | Variable definitions:
65  | On_off(I) ... State of unit I 0=off, 1=on
70  | Units ... Label for softkey
75  | Strain_1(), Strain_2() ... Readings from units 1 & 2
80  | Tyme_1(), Tyme_2() ... Time of readings
85  | T_0() ... Start time from system
90  | T_e() ... Elapsed time
95  | T_i() ... Clock time
100 | Rdg() ... Counter for readings
105 PRINT X_t$,X_d$
110 GOTO Main_menu
115 Set_up: 1
120 Rdg(1)=0
125 Rdg(2)=0
130 GOTO 1
135 GINIT
140 INPUT "Specify max time (seconds) for test 1",Max_time_1
145 Lvd_t_cal_1=-.1 inches per volt
150 INPUT "Specify LVDT 1 calibration (default .1 in/V)",Lvd_t_cal_1
155 Gage_1=.5
160 INPUT "Specify #1 spec. gage length, inches.(Default=.5)",Gage_1
165 INPUT "Specify max time (seconds) for test 2",Max_time_2
170 Lvd_t_cal_2=-.1 inches per volt
175 INPUT "Specify LVDT 2 calibration (default .1 in/V)",Lvd_t_cal_2
180 Gage_2=.5
185 INPUT "Specify #2 spec. gage length, inches.(Default=.5)",Gage_2
190 Max_time=0
195 IF Max_time_1>Max_time AND Max_time_1>Max_time_2 THEN
200   Max_time=Max_time_1
205 ELSE
210   Max_time=Max_time_2
215 END IF
220 Min_strain=0
225 INPUT "Specify min % strain desired (Default=0)",Min_strain
230 INPUT "Specify max % strain desired",Max_strain
235 P_strain=Max_strain-Min_strain
240 GRAPHICS ON
245 VIEWPORT 0,100,10,100
250 WINDOW =Max_time+.1,Max_time,Min_strain-.1,R_strain,Max_strain+.1,R_strain
255 CLIP 0,Max_time,Min_strain,Max_strain
260 AXES Max_time/10,R_strain/10,0,Min_strain
265 CLIP OFF
270 LOPS 6
275 CSIZE 3
280 IF Max_time<1000 THEN Step_time=10
285 IF Max_time>1000 THEN Step_time=5
290 FOR I=0 TO Max_time STEP Max_time/Step_time
295   MOVE I,Min_strain+.05*R_strain
300   LABEL USING "K":I
305 NEXT I
310 MOVE Max_time/2,Min_strain-.1*R_strain
315 LABEL USING "K":I"Time, seconds"
320 LOPS 8

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves

```

325 FOR I=Min_strain TO Max_strain STEP R_strain/10
330 MOVE -.01*Max_time,I
335 LABEL USING "K":I
340 NEXT I
345 MOVE -.09*Max_time,R_strain/2+Min_strain
350 LOGS 5
355 OEG
360 LDIR 90
365 IF Strain_type=2 THEN LABEL USING "K": "% Strain"
370 IF Strain_type=1 THEN LABEL USING "K": "% True Strain"
375 LOIR 0
380 LOGS 5
385 PRINTER IS 1
390 FOR I=1 TO 2
395 On_off(I)=0
400 Units(I)=" "%VALS(I)&" is OFF"
405 T_0(I)=1.E-99
410 NEXT I
415 Tyme_int_1=(Max_time_1/4999) !Sets up time
420 Tyme_int_2=(Max_time_2/4999) !intervals
425 Main_menu: I
430 GOTO Keys_setup
435 Main_menu_1: I
440 GOSUB Time_interval
445 Main_menu_idle: GOTO Main_menu_1
450 Keys_setup: I
455 OFF KEY
460 ON KEY 0 LABEL Units(1) GOTO Unit_1_on_off
465 ON KEY 1 LABEL "Print 1" GOTO Print_1
470 ON KEY 2 LABEL "Plot1" GOTO Dis_plot_1
475 ON KEY 3 LABEL "Sto/Rec1" GOTO Sto_rec_1
480 ON KEY 4 LABEL "New Test" GOTO Set_up
485 ON KEY 5 LABEL Units(2) GOTO Unit_2_on_off
490 ON KEY 6 LABEL "Print 2" GOTO Print_2
495 ON KEY 7 LABEL "Plot2" GOTO Dis_plot_2
500 ON KEY 8 LABEL "Sto/Rec2" GOTO Sto_rec_2
505 ON KEY 9 LABEL "QUIT" GOTO Quitter
510 Key_setup_1: I
515 GOTO Main_menu_1
520 Unit_1_on_off: !Select unit 1 for change
525 I=1
530 GOTO Units_on_off
535 Unit_2_on_off: !Select unit 2 for change
540 I=2
545 Units_on_off: !Turn unit(I) on/off
550 IF On_off(I)=0 THEN
555 On_off(I)=1
555 T_0(I)=TIMEDATE
565 I
570 I
575 ! NOTE: 10 volts = 1 inch movement
580 I
585 I
590 IF I=1 THEN
595 PRINT "Set LVDT unit one to 0 and press return"
600 BEEP 200,.1
605 INPUT Whichs
610 OUTPUT 709:"VRS11"
615 T_0(I)=TIMEOATE
615 ENTER 709:Lvd:1
620 ELSE
625 PRINT "Set LVDT unit two to 0 and press return"
630 BEEP 200,.1
635 INPUT Whichs
640 OUTPUT 709:"VRS12"
645 T_0(I)=TIMEDATE

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```

645     ENTER T09:Lvdt2
650     END IF
655     Unit$(I) = "%3VALS(I)/3" is ON"
660 ELSE
665     On_off(I)=0
670     Unit$(I) = "%3VALS(I)&" is OFF"
675 END IF
680 GOTO Keys_setup
685 Print_1: 1Print data from unit 1
690 I=1
695 GOTO Print_data
700 Print_2: 1Print data from unit 2
705 I=2
710 Print_data: 1Hardcopy of data points
715 PRINTER IS 705
720 PRINT
725 PRINT
730 PRINT "Unit : "I;" ";TIME$DATE
735 PRINT "      :      Strain, %      Time, minutes      :      Strain, %      Ti
me, minutes"
740 FOR J=1 TO Nr_pts-1 STEP 2
745 PRINT USING Fmt1;J;Strain(I,J);Tyme(I,J);J+1;Strain(I,J+1);Tyme(I,J+1)
750 NEXT J
755 Fmt1: IMAGE 2(50,5X,0.000ESZ,5X,0.000ESZ,7X)
760 GOTO Keys_setup
765 Dis_plot_1: 1
770 I=1
775 Dis_plot_3: 1
780 GOSUB Which_plotn
785 GOSUB Plot_on
790 GOTO Main_menu
795 Dis_plot_2: 1
800 I=2
805 GOTO Dis_plot_3
810 Which_plotn: 1
815 FOR Q=0 TO 4
820 ON KEY Q LABEL "CRT" GOTO Plotn_crt
825 ON KEY Q-5 LABEL "Plotter" GOTO Plotn_plotn
830 NEXT Q
835 Wh_plotn_spin: GOTO Wh_plotn_spin
840 Plotn_crt: 1
845 IF I=1 THEN Plotn_1$="CRT"
850 IF I=2 THEN Plotn_2$="CRT"
855 RETURN
860 Plotn_plotn: 1
865 IF I=1 THEN Plotn_1$="Plotter"
870 IF I=2 THEN Plotn_2$="Plotter"
875 RETURN
880 Plot_on: 1
885 Which_strain: 1
890 INPUT "1=True strain or 2=engineering strain?",Strain_type
895 IF Strain_type<1 OR Strain_type>2 THEN Which_strain
900 Min_strain=0
905 INPUT "Specify minimum strain desired (Default=0)",Min_strain
910 INPUT "Specify maximum strain desired",Max_strain
915 Min_time=0
920 INPUT "Specify minimum time desired (Default=0)",Min_time
925 INPUT "Specify maximum time desired",Max_time
930 PRINT "Strain axis:";Min_strain;"-";Max_strain
935 PRINT "Time axis:";Min_time;"-";Max_time
940 PRINT "Is this OK?"
945 GOSUB Yes_no
950 IF Answers="N" THEN Plot_on
955 GOCLEAR
960 GRAPHICS ON
965 GOSUB Which_plotn

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```

970 IF (Plotr_1$="CRT" AND I=1) OR (Plotr_2$="CRT" AND I=2) THEN
975   ALPHA OFF
980   PLOTTER IS 3,"INTERNAL"
985 ELSE
990   PLOTTER IS 705,"HPGL"
995 END IF
1000 IF (Plotr_1$="CRT" AND I=1) OR (Plotr_2$="CRT" AND I=2) THEN
1005   VIEWPORT 0,125,20,90
1010 ELSE
1015   VIEWPORT 0,125,12,95
1020 END IF
1025 R_time=Max_time-Min_time
1030 R_strain=Max_strain-Min_strain
1035 WINDOW Min_time-.1*R_time,Max_time,Min_strain+.1*R_strain,Max_strain
1040 CLIP Min_time,Max_time,Min_strain,Max_strain
1045 AXES R_time/10,R_strain/10,Min_time,Min_strain
1050 CLIP OFF
1055 CSIZE 3
1060 IF Max_time<=1000 THEN Step_time=10
1065 IF Max_time>1000 THEN Step_time=5
1070 LORG 6
1075 FOR J=Min_time TO Max_time STEP R_time/Step_time
1080   MOVE J,Min_strain-.015*R_strain
1085   LABEL USING "K";J
1090 NEXT J
1095 MOVE Min_time+.5*R_time,Min_strain-.09*R_strain
1100 LABEL USING "K";"Time, seconos"
1105 LORG 8
1110 OES
1115 FOR J=Min_strain TO Max_strain STEP R_strain/10
1120   MOVE Min_time+.03*R_time,J
1125   LABEL USING "K";J
1130 NEXT J
1135 LOIR 30
1140 LORG 5
1145 MOVE Min_time+.09*R_time,Min_strain+.5*R_strain
1150 IF Strain_type=2 THEN
1155 LABEL USING "K";"% Strain"
1160 ELSE
1165 LABEL USING "K";"True Strain"
1170 END IF
1175 LOIR 0
1180 Iplot=0
1185 OFF KEY
1190 CLIP Min_time,Max_time,Min_strain,Max_strain
1195 FOR J=1 TO 5000
1200   IF J<>1 THEN O1_tyme=Tyne_x
1205   Strayn=0
1210   Tyne_x=0
1215   IF I=1 THEN
1220     Strayn=Strain_1(J)
1225     Tyne_x=Tyne_1(J)
1230   ELSE
1235     Strayn=Strain_2(J)
1240     Tyne_x=Tyne_2(J)
1245   END IF
1250 ON ERROR GOTO 1260
1255 IF Strain_type=1 THEN Strayn=LOG(1+(Strayn/100))
1260 OFF ERROR
1265 IF Tyne_x<Min_time THEN Plot_next
1270 IF Tyne_x>Max_time THEN
1275   J=5000
1280   GOTO Plot_next
1285 END IF
1290 Iplot=Iplot+1
1295 IF Iplot=1 THEN MOVE x,Strayn

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```

1300 IF Iplot<>1 AND (Tyme_x=0 AND Strayn=0) OR O1_tyme/Tyme_x THEN Plot_next
1305 IF J<>1 AND Strayn=0 AND Tyme_x=0 THEN Plot_next
1310 DRAW Tyme_x,Strayn
1315 Plot_next: NEXT J
1320 IF Plotn_1$="CRT" OR Plotn_2$="CRT" THEN
1325 PENUP
1330 ELSE
1335 PEN 0
1340 END IF
1345 RETURN
1350 Yes_no: 1
1355 FOR Q=0 TO 4
1360 ON KEY Q LABEL "Yes" GOTO Yess
1365 ON KEY Q+S LABEL "No" GOTO Noo
1370 NEXT Q
1375 Yes_no_idle: GOTO Yes_no_idle
1380 Yess: 1
1385 Answers="Y"
1390 GOTO Yes_no_ret
1395 Noo: 1
1400 Answers="N"
1405 Yes_no_ret: 1
1410 OFF KEY
1415 RETURN
1420 Sto_rec_1: 1
1425 I=1
1430 GOTO Store_recall
1435 Sto_rec_2: 1
1440 I=2
1445 GOTO Store_recall
1450 Store_recall: 1
1455 OFF KEY
1460 FOR Q=0 TO 4
1465 ON KEY Q LABEL "SaveData" GOTO Store_1
1470 ON KEY Q+S LABEL "Rec.Data" GOTO Recall_1
1475 NEXT Q
1480 Store_recall_1: GOTO Store_recall_1
1485 Store_1: 1 Stores data
1490 INPUT "File name for data storage",F_names$
1495 GOSUB Which_disk
1500 ON ERROR GOTO Store_error
1505 Store_2: 1
1510 CREATE BOAT F_names$&"_Y",1,40000
1515 CREATE BOAT F_names$&"_Y",1,40000
1520 CREATE BOAT F_names$&"_I",1,4000
1525 Store_2_y: 1
1530 OFF ERROR
1535 Err_eof=1
1540 ON ERROR GOTO Eof_error
1545 ASSIGN @File_x TO F_names$&"_Y"
1550 IF I=1 THEN OUTPUT @File_x:Tyme_1(*)
1555 IF I=2 THEN OUTPUT @File_x:Tyme_2(*)
1560 Err_eof_1: 1
1565 ASSIGN @File_x TO *
1570 Err_eof=2
1575 ASSIGN @File_y TO F_names$&"_Y"
1580 IF I=1 THEN OUTPUT @File_y:Strain_1(*)
1585 IF I=2 THEN OUTPUT @File_y:Strain_2(*)
1590 Err_eof_2: 1
1595 ASSIGN @File_y TO *
1600 Err_eof=3
1605 ASSIGN @File_z TO F_names$&"_I"
1610 OUTPUT @File_z:I,T_0(*),T_e(*),T_1(*),Rdg(*),Max_time_1,Max_time_2
1615 Err_eof_3: 1
1620 ASSIGN @File_z TO *
1625 OFF ERROR

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```

1630 GOTO Main_menu
1635 Eof_error: !
1640 OFF ERROR
1645 ON ERROR GOTO Eof_error
1650 IF Err_eof=1 THEN Err_eof_1
1655 IF Err_eof=2 THEN Err_eof_2
1660 IF Err_eof=3 THEN Err_eof_3
1665 GOTO Main_menu
1670 Which_disk: !
1675 OFF KEY
1680 FOR Q=0 TO 9
1685   ON KEY Q LABEL "" GOTO Which_disk_spin
1690 NEXT Q
1695 ON KEY 0 LABEL "82901-0" GOTO Drive_0
1700 ON KEY 1 LABEL "82901-1" GOTO Drive_1
1705 ON KEY 9 LABEL "INTERNAL" GOTO Drive_1
1710 Which_disk_spin: GOTO Which_disk_spin
1715 Drive_0: !
1720 MASS STORAGE IS ":HP82901,700"
1725 RETURN
1730 Drive_1: !
1735 MASS STORAGE IS ":HP82901,700,1"
1740 RETURN
1745 Drive_1: !
1750 MASS STORAGE IS ":INTERNAL"
1755 RETURN
1760 Store_error: !
1765 IF ERRN=54 THEN
1770   PRINT "Duplicate file name. Shall I overwrite?"
1775   GOSUB Yes_no
1780   OFF ERROR
1785   IF Answer$="Y" THEN Store_2_y
1790 ENO IF
1795 IF ERRN=54 THEN
1800   PRINT "Disk is full. Change disk or mass storage unit."
1805   BEEP 200,.5
1810   OFF ERROR
1815   GOTO Store_1
1820 ENO IF
1825 IF ERRN=80 THEN
1830   PRINT "Shut the bloomin' disk drive. It's cold out there!"
1835   OFF ERROR
1840   GOTO Store_1
1845 ENO IF
1850 IF ERRN=85 THEN
1855   INITIALIZE ":MSUS$
1860   OFF ERROR
1865   GOTO Store_2
1870 ENO IF
1875 IF ERRN=90 THEN
1880   PRINT "Mass storage system error. Select another disk drive."
1885   OFF ERROR
1890   GOTO Store_1
1895 ENO IF
1900 PRINT "Error: ";ERRN
1905 OFF ERROR
1910 GOTO Main_menu
1915 Recall_1: !
1920 INPUT "File name to be recalled (omit suffixes)",F_name$
1925 PRINT "Which disk drive?"
1930 GOSUB Which_disk
1935 ASSIGN @File_x TO F_name$&"_x"
1940 ON ERROR GOTO 1955
1945 IF I=1 THEN ENTER @File_x;Type_1(0)
1950 IF I=2 THEN ENTER @File_x;Type_2(0)
1955 ASSIGN @File_x TO *

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)


```

1960 OFF ERROR
1965 ON ERROR GOTO 1985
1970 ASSIGN @File_y TO F_names&"_Y"
1975 IF I=1 THEN ENTER @File_y;Strain_1(*)
1980 IF I=2 THEN ENTER @File_y;Strain_2(*)
1985 ASSIGN @File_y TO *
1990 OFF ERROR
1995 ON ERROR GOTO 2010
2000 ASSIGN @File_z TO F_names&"_Z"
2005 ENTER @File_z;I,T_0(*),T_e(*),T_i(*),Rdg(*),Max_time_1,Max_time_2
2010 ASSIGN @File_z TO *
2015 OFF ERROR
2016 Factor=1
2018 INPUT "Specify multiplication factor for data. Def=1",Factor
2019 IF Factor=1 THEN
2020   GOSUB Plot_on
2021 ELSE
2022   FOR J=1 TO 5000
2023     IF I=1 THEN Strain_1(J)=Strain_1(J)*Factor
2024     IF I=2 THEN Strain_2(J)=Strain_2(J)*Factor
2025   NEXT J
2027 GOSUB Plot_on
2028 ENO IF
2030 Quitter: 1
2031 BEEP 2000,.1
2035 FOR Q=0 TO 4
2040   ON KEY C LABEL "QUIT" GOTO Quitter_1
2045   ON KEY C+S LABEL "Continue" GOTO Keys_setup
2050 NEXT Q
2055 Quitter_idle: GOTO Quitter_idle
2060 Quitter_1: STOP
2065 Time_intervals: 1
2070 IF On_off(1)=0 THEN Time_int_1
2075 T_e(1)=TIMEDATE-T_0(1)
2080 IF T_e(1)>Rdg(1)*Time_int_1 THEN GOSUB Read_1
2085 Time_int_1: 1
2090 IF On_off(2)=0 THEN RETURN
2095 T_e(2)=TIMEDATE-T_0(2)
2100 IF T_e(2)>Rdg(2)*Time_int_2 THEN GOSUB Read_2
2105 RETURN
2110 Read_1: 1
2115 Rdg(1)=Rdg(1)+1
2120 IF Rdg(1)>5000 THEN
2125   Rdg(1)=5000
2130   RETURN
2135 ENO IF
2140 IF Rdg(1)=1 THEN
2145   GOSUB Display_1_on
2150 ENO IF
2155 IF T_e(1)>Max_time_1 THEN
2160   On_off(1)=0
2165   ON KEY 0 LABEL "#1 DONE" GOTO Unit_1_on_off
2170 ENO IF
2175 OUTPUT 709;"URSAI1"
2180 ENTER 705;Strain_1(Rdg(1))
2185 Strain_1(Rdg(1))=100*Lvd1_cal_1*(Strain_1(Rdg(1))-Lvd1)/Gage_1
2190 Time_1(Rdg(1))=T_e(1)
2195 LOG 5
2200 CSIZE 2
2205 IF Strain_type=2 THEN
2210   MOVE Time_1(Rdg(1)),Strain_1(Rdg(1))
2215 ELSE
2220   ON ERROR GOTO 2230
2225   MOVE Time_1(Rdg(1)),LOG(Strain_1(Rdg(1))+1)
2230 OFF ERROR
2235 ENO IF

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```

2240 LABEL USING "K": "1"
2245 RETURN
2250 Read_2: 1
2255 Rdg(2)=Rdg(2)+1
2260 IF Rdg(2)>E000 THEN
2265 Rdg(2)=E000
2270 RETURN
2275 ENO IF
2280 IF Rdg(2)=1 THEN
2285 GOSUB Display_2_on
2290 ENO IF
2295 IF T_e(2)>Max_time_2 THEN
2300 On_off(2)=0
2305 ON KEY 5 LABEL "#2 DONE" GOTO Unit_2_on_off
2310 ENO IF
2315 OUTPUT 709:"URSA12"
2320 ENTER 709:Strain_2(Rdg(2))
2325 Strain_2(Rdg(2))=100*Lvdt_cal_2*(Strain_2(Rdg(2))-Lvdt2)/Gage_2
2330 Tyme_2(Rdg(2))=T_e(2)
2335 LOG S
2340 CSIZE 2
2345 IF Strain_type=2 THEN
2350 MOVE Tyme_2(Rdg(2)),Strain_2(Rdg(2))
2355 ELSE
2360 ON ERROR GOTO 2370
2365 MOVE Tyme_2(Rdg(2)),LOG(Strain_2(Rdg(2))+1)
2370 OFF ERROR
2375 ENO IF
2380 LABEL USING "K": "2"
2385 RETURN
2390 Display_1_on: 1
2395 Disp_1=1
2400 BEEP 2000,,1
2405 RETURN
2410 Display_2_on: 1
2415 Disp_2=1
2420 RETURN
2425 ENO

```

Figure 68. Computer Program to Acquire Creep Data and Plot Creep Curves (Continued)

```

10  ! PROGRAM TO COMPUTE STRAIN RATES GIVEN THE DATA DISC FROM A TEMPERATURE C
CYCLING TEST.
30  ! IT IS USER FRIENDLY AND MENU-DRIVEN.
40  !WRITTEN 10-19-89 BY LT EARL F. GOODSON,SR.
50  !EDITED 10-21-89 BY LT EARL F. GOODSON,SR.
60  DIM Strain_1(5000),Tyme_1(5000),True_strain(5000),Str_rate(1000),A_str(100
0)
71  DIM Log_rate(2000)
80  Nr_pnts=5000
81  PRINTER IS 1
90  I=1
100 PRINT "PROGRAM TO CALC STRAIN RATES GIVEN THE DATA DISC FROM A TEMPERATURE
CYCLING TEST."
110 PRINT " HIT CONTINUE TO BEGIN"
111 PAUSE
113 GOTO Keys_setup
114 Disc: 1
115 OFF ERROR
120 PRINT "PLACE DATA DISC IN THE INTERNAL DRIVE."
130 INPUT "FILENAME TO BE RECALLED(OMIT SUFFIXES)",F_names
131 ON ERROR GOTO Disc
140 MASS STORAGE IS ":INTERNAL" ! RECOVERS TIME
150 ! DATA ARRAY
160 !
170 ASSIGN @File_x TO F_names&"_X"
180 ON ERROR GOTO 200
190 ENTER @File_x:Tyme_1(*)
200 ASSIGN @File_x TO *
210 OFF ERROR
220 ON ERROR GOTO 270
230 ASSIGN @File_y TO F_names&"_Y"! RECOVERS ENG
240 ! STRAIN DATA ARRAY
250 !
260 ENTER @File_y:Strain_1(*)
270 ASSIGN @File_y TO *
280 OFF ERROR
351 GOTO See_all
360 !
370 !ASSIGNS TRUE STRAIN VALUES AN ARRAY NUM.
380 !
381 See_all: 1
383 Q=0
384 PRINT "PLEASE WAIT UNTIL THIS MESSAGE DISAPPEARS. THE TRUE STRAIN ARRAY I
S BEING FILLED"
390 FOR J=1 TO 4999 STEP 1 ! FILLS TRUE STRAIN ARRAY
391 Q=Q+1
400 True_strain(Q)=LOG(1+(Strain_1(J)/100))
401 IF True_strain(Q)=0 THEN GOTO 421
410 NEXT J
421 OUTPUT 2;"K";
422 GOTO Keys_setup
430 !
440 !
450 !SOFT KEY SET-UP FOR MAIN MENU
460 !
470 !
480 Keys_setup: 1
481 OUTPUT 2;"K"; ! CLEAR SCREEN CMO
490 OFF KEY
500 ON KEY 0 LABEL "PRN E,T" GOTO Print_1
510 ON KEY 1 LABEL "PL/PR ER" GOTO Strain_rate_1
520 !ON KEY 2 LABEL "CALC DIF" GOTO DIFF_COMP
530 ON KEY 3 LABEL "OSURC" GOTO Act_end

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables

```

540 ON KEY 4 LABEL "QUIT" GOTO Quitter
541 ON KEY 5 LABEL "NEWTEST" GOTO Disc
550 Key_idle: GOTO Key_idle
560 I
570 I SUBPROCEDURE TO PRINT ALL STRAINS AND TIME
580 I ON THE PRINTER
590 I
600 I
610 Print_1: I
620 IPRINT "PRINT_1 ENTERED" I PRINTS TRUE STRAINS AND TIMES
626 Strt1=2
627 Stp1=4999
628 Intv1=2
531 INPUT "INPUT RDG TO START AT,(DEFAULT = 1ST RDG)",Strt1
632 INPUT "RDG TO STOP ON,(DEFAULT = 4999)",Stp1
633 INPUT "INPUT INTERVAL TO CALC TRUE STRAINS,(DEF=2 RDGS)",Intv1
634 PRINTER IS 706
635 PRINT "FILENAME IS ";F_name$
637 PRINT " RDG # TRUESTRAIN TIME,SEC RDG # TRUESTRAIN
TIME,SEC"
639 FOR J=Strt1 TO Stp1 STEP Intv1*2
640 PRINT USING Fmt1;J;True_strain(J);Time_1(J);J+Intv1;True_strain(J+Intv1)
;Time_1(J+Intv1)
641 ON ERROR GOTO 644
642 NEXT J
643 Fmt1: IMAGE 2(1SD,SX,SD.ODDDESZZ,SX,SD.ODDDESZZ,7X)
644 PRINTER IS I
645 OFF ERROR
646 GOTO Keys_setup
647 I
650 I
660 I SUBPROCEDURE TO PRINT AN INTERVAL OF ALL
670 I STRAIN RATES AND STRAINS WITH PLOTTING
680 I
690 I
700 Strain_rate_1: I
701 PRINTER IS I
702 Interv=10
704 Strt=2
705 Stp=1900
706 Ans_1$= "N"
707 Prt=1
708 Ans$="Y"
709 Tr=0
712 INPUT "INPUT INTERVAL BETWEEN STRAIN RATES,(DEF=10 RDGS)",Interv
713 I=Interv
715 INPUT "INPUT VALUE TO START AT,(DEFAULT=1ST RDG)",Strt
720 INPUT "INPUT VALUE TO STOP AT,(DEFAULT=1900 RDG)",Stp
721 INPUT "DO YOU WANT A HARD COPY OF DATA?(DEFAULT=NO)",Ans_1$
722 IF Ans_1$="Y" THEN
725 INPUT "HIT ENTER FOR CRT OR 2 FOR EXT PRINTER,(DEF=CRT)",Prt
725 END IF
729 PRINT "ARE YOU SURE YOU WANT TO START AT ";Strt: " , STOP AT ";Stp" OVER I
INTERVAL OF ";Interv
730 INPUT "INPUT Y/N,(DEFAULT=YES)",Ans$
731 IF Ans$="N" THEN
732 GOTO Strain_rate_1
733 OUTPUT 2;"X"
734 ELSE
735 PRINT "PLEASE WAIT FOR MENU TO APPEAR. STRAIN RATE APRAY IS BEING FILLE
D."
736 END IF
737 IF Prt=2 THEN PRINTER IS 706
738 IF Ans_1$="Y" THEN
740 PRINT "FILENAME IS ";F_name$
741 PRINT " INTERVAL AVG STRAIN STRAIN RATE*1 INTERVAL AVG ST

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```

RAIN      STRAIN R"
742      END IF
750      FOR J=Strt TO Sto STEP Interv
751          Tr=Tr+1
760          Str_rate(Tr)=ABS(((True_strain(J+Interv)-True_strain(J))/(Tyme_1(J+Inter
v)-Tyme_1(J))))
761          Log_rate(Tr)=LGT(ABS(Str_rate(Tr)))
770          A_str(Tr)=(True_strain(J+Interv)+True_strain(J))/2
780          ON ERROR GOTO 830
800          IF Ans_1$="Y" THEN
801              PRINT USING Fmt2;J;" ";J+1;A_str(Tr);Str_rate(Tr);J+1;" ";J+2;1;A_str(1
+Tr);Str_rate(1+Tr);
804          END IF
810          NEXT J
820      Fmt2:      IMAGE (40,K,40,5X,50.000ESZZ,5X,50.000ESZZ,3X)
830      OFF ERROR
840      PRINTER IS 1
850      OFF KEY
851      OUTPUT 2;"K";
860      ON KEY 1 LABEL "PLOT ER,E" GOTO Plot_er
861      ON KEY 2 LABEL "NEWTEST" GOTO 0:isc
862      ON KEY 3 LABEL "MENU" GOTO Keys_setup
863      ON KEY 4 LABEL "SLOPE" GOTO Sloper
870      Plot_idle:      GOTO Plot_idle
880      GOTO Keys_setup
890      I
900      I
910      SUB TO PLOT STRAIN RATE VS STRAIN
920      Plot_er:      I
921      OFF KEY
922      Ans4$="N"
924      Ylog=0      I TELLS PLOT TO USE REG Y-AXIS
925      PRINT "THIS SECTION GIVES YOU SEVERAL CHOICES OF PLOTS. YOU MAY NEED IT
ERATION TO GET THE"
926      PRINT "SCALE AND THE LIMITS RIGHT. DEFAULT IS A SEMI-LOG PLOT. YOU ALS
O CAN PLOT REGULAR"
927      PRINT "AXES. AUTO SCALING REQUIRES SOME PATIENCE SINCE IT USES YMAX AND
YMIN, SO TRY AGAIN"
928      PRINT
932      X1$="TRUE STRAIN,IN/IN"
940      Y1$="LOG STRAIN RATE"
950      T$="TEMP CYCLING EXP"
951      INPUT "PLOT LOG STRAIN RATE WITH REG AXES?,(DEF=NO)",Ans4$
953      IF Ans4$="N" THEN
954          Ylog=1
955          Y1$="STRAIN RATE,SEC-1"
956          X1$="TRUE STRAIN,IN/IN"
958      INPUT "PLOT SEMI-LOG W/Y AS LOG AXIS?,(YES=DEF,N0=0)",Ylog
961      END IF
962      Ans2=1
963      INPUT "INPUT TITLE OF PLOT(DEF=TEMP CYCL EXP)",T$
965      INPUT "1 FOR CRT OR 2 FOR EXT PLOT,(DEF=CRT)",Ans2
966      IF Ans2=2 THEN
967          PLOTTER IS 705,"HP6L"
968      ELSE
969          GCLEAR
970          ALPHA OFF
971          GRAPHICS ON
972      END IF
973      IF Ans4$="Y" THEN
974          CALL Auscl(Log_rate(1),Log_rate(Tr),0,Mn_r,Mx_r,Tc_r)
975      ELSE
976          CALL Auscl(Str_rate(1),Str_rate(Tr),0,Mn_r,Mx_r,Tc_r)
977      END IF
980      CALL Auscl(A_str(1),A_str(Tr),0,Mn_e,Mx_e,Tc_e)
984      IF Ans4$="Y" THEN

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```

990      CALL Plot(Mn_e,Mx_e,Mn_r,Mx_r,Tc_e,Tc_r,0,Ylog,Xis,Yis,A_str(*),Log_ra
tel(*),Tr,Ts)
991      ELSE
992      CALL Plot(Mn_e,Mx_e,Mn_r,Mx_r,Tc_e,Tc_r,0,Ylog,Xis,Yis,A_str(*),Str_ra
tel(*),Tr,Ts)
993      END IF
995      PRINTER IS 1
996      PRINT "HIT CONTINUE TO RESUME THE PROGRAM"
997      PAUSE
998      GINIT
999      GCLEAR
1000     GRAPHICS OFF
1001     ALPHA ON
1002     GOTO Keys_setup
1010     !
1020     ! SUB TO PRINT DESIGNATED STRAIN RATES
1030     !
1040 Act_ener: !
1050     PRINT "ACT_ENER ENTERED"
1051     Ans7s="Y"
1052     INPUT "INPUT TEMP 1",T1
1053     INPUT "INPUT STRAIN RATE 1",S1
1054     INPUT "INPUT TEMP 2",T2
1055     INPUT "INPUT STRAIN RATE 2",S2
1056     Qsubc=(2.303*1.58)*(LGT(S1)-LGT(S2))/((1/(T1+273))-(1/(T2+273)))
1057     PRINT "ACTIVATION ENERGY = ":Qsubc
1058     INPUT "DO YOU WANT TO GO AGAIN(DEF=YES)",Ans7s
1059     IF Ans7s="Y" THEN GOTO Act_ener
1061     GOTO keys_setup
1070     !
1080     ! SUB TO PRINT DESIGNATED STRAINS
1090 Sloper: !
1100     PRINT "SLOPER ENTERED"
1110     GOTO Keys_setup
1120     !
1130     ! SUB TO QUIT STRAIN RATE PROGRAM
1140 Quitter: !
1150     BEEP 2000,.1
1160     FOR Q=0 TO 4
1170         ON KEY Q LABEL "QUIT" GOTO Quitter_1
1180         ON KEY Q+S LABEL "CONTINUE" GOTO Keys_setup
1190     NEXT Q
1200 Quitter_idle: GOTO Quitter_idle
1210 Quitter_1: STOP
1220     END
1221     !
1222     !
1230 SUB Auscl(Min,Max,Offset,Minm,Maxm,Tick) ! 5825 12/02/81
1240 !PRINT "AUTO-SCALE ENTERED"
1241     !
1250     INTEGER Power,N,Dir
1260     Range=ABS(Max-Min)
1270     Power=INT(LGT(Range))
1280     Norm=Range/10^Power
1290     N=10*(Norm=.5)+5*((Norm<.5) AND (Norm>.2))+2*((Norm<.2) AND (Norm>.1))+1
1300     Inter=ROUND(N*10^(Power-1),1)
1310     Dir=SGN(Max-Min)
1320     X=(Min-Offset)/10^Power
1330     GOSUB Rout
1340     Minm=Out*10^Power+Offset
1350     Dir=SGN(Max-Min)
1360     Y=(Max-Offset)/10^Power
1370     GOSUB Rout
1380     Maxm=Out*10^Power+Offset
1390     Tick=ROUND(ABS(Maxm-Minm)/Inter+1,INT(LGT(ABS((Maxm-Minm)/Inter)+1)))

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)


```

1430 GOTO Exit
1440 Rout=Test=ABS(X)-INT(ABS(X)) ! ROUND X TO MULTIPLE OF N IN DIRECTION Dir.
1450 Digit=INT(10*Test)
1460 Delta=Digit*(N=10)+Digit MOD N*(N<10)
1470 Round=((SGN(X)*Dir+0)*N-SGN(X)*Dir+Delta)/10*(Test-Digit/10 OR Delta)<>0
1480 IF ABS(SGN(X)*Digit/10+Dir+Round)>1 THEN Round=1-Digit/10
1490 Rout=SGN(X)*(INT(ABS(X))+Digit/10)+Dir+Round
1500 RETURN
1550 Exit: SUBEND
1560 !
1570 !
2270 SUB Plot(Xmin,Xmax,Ymin,Ymax,Xtic,Ytic,Xlog,Ylog,(S,YS,X(*),Y(*),N,Titles
2280 ! 3825 01/26/82
2290 !PRINT "PLOTTER ENTERED"
2291 !
2300 INTEGER Pointn,Minor,Majtic,Mintic,Penc
2310 DEG
2320 NI=INT(ABS(N))
2530 Xmajor=INT(ABS(Xtic)) ! VARIABLE SETUP
2540 Ymajor=INT(ABS(Ytic))
2550 Cxmax=Xmax
2560 IF Xlog THEN Cxmax=LGT(Xmax)
2570 Cxmin=Xmin
2580 IF Xlog THEN Cxmin=LGT(Xmin)
2590 Cymax=Ymax
2591 Y1=(1.E-9+Ymax)
2600 IF Ylog THEN Cymax=LGT(Y1)
2610 Cymin=Ymin
2611 Y2=(1.E-9+Ymin)
2620 IF Ylog THEN Cymin=LGT(Y2)
2630 IF Cxmin<Cxmax THEN GOTO X_ok ! MAKE SURE Max > Min
2640 Dummy=Cxmin
2650 Cxmin=Cxmax
2660 Cxmax=Dummy
2670 X_ok: IF Cymin<Cymax THEN GOTO Y_ok
2680 Dummy=Cymin
2690 Cymin=Cymax
2700 Cymax=Dummy
2710 Y_ok: Cheight=15/4.54 ! CHARACTER SIZE AND TICK LENGTH IN GOU
2720 Cwidth=.5*Cheight
2730 Tick=Cwidth
2740 IF RATIO>1 THEN !CALC VERT. AND HORIZ. LIMITS IN GOU
2750 Vert=100
2760 Horiz=RATIO*100
2770 ELSE
2780 Horiz=100
2790 Vert=100/RATIO
2800 END IF
2810 Gdux=Horiz-10*Cwidth-Cheight-Tick ! AXIS LENGTH IN GOU
2820 Gduy=Vert-3.5*Cwidth-2.5*Cheight-Tick
2830 ! CONVERT HARD LIMITS 0,Horiz TO DATA UNITS Xlower, Xupper, etc.
2840 Xlower=Cxmin-(9.5*Cwidth+Cheight+Tick)/Gdux*(Cxmax-Cxmin)
2850 Xupper=Cxmax+.5*Cwidth/Gdux*(Cxmax-Cxmin)
2860 Ylower=Cymin-(Cheight+9.5*Cwidth+Tick)/Gduy*(Cymax-Cymin)
2870 Yupper=Cymax+.5*Cheight/Gduy*(Cymax-Cymin)
2880 Xticlen=Tick/Gduy*(Cymax-Cymin)
2890 Yticlen=Tick/Gdux*(Cxmax-Cxmin)
2900 VIEWPORT 0,Horiz,0,Vert ! SETUP PLOTTING PARAMETERS.
2910 PIVOT 0
2920 MOVE 0,0
2930 WINDOW Xlower,Xupper,Ylower,Yupper
2940 CSIZE Cheight,Cwidth/Cheight
2950 CLIP Cxmin,Cxmax,Cymin,Cymax
2960 IF Xmajor=0 THEN GOTO Y_axis
2970 Minor=INT(10*(ABS(Xtic)-Xmajor)) !PLOT X AXIS
2980 Tickspace=Cxmax-Cxmin

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```

2990 IF Xmajor>1 THEN Tickspace=(Cxmax-Cxmin)/(Xmajor-1)
3000 MOVE Cxmin,Cymin
3010 ORAW Cxmax,Cymin
3020 LOG 8
3030 LOIR 0
3040 FOR Majtic=1 TO Xmajor
3050   Majpos=Cxmin+Tickspace*(Majtic-1)
3060   MOVE Majpos,Cymin-(tictlen
3070   Labl=Majpos
3080   IF Xlog THEN Labl=10^Majpos
3090   IF ((ABS(Labl))>=1.E+6) OR (ABS(Labl)<1.E-4) AND (Labl<>0) THEN GOTO F1
oatx
3100   IF Labl<>0 THEN
3110     Temp=-INT(LGT(ABS(Labl)))-1
3120     IF Temp<=0 THEN Temp=0
3130     Labl=OROUND(Labl,7-Temp)
3140   END IF
3150   CLIP OFF
3160   LABEL USING "*,K":Labl
3170   CLIP ON
3180   PENUP
3190   GOTO Xticmark
3200 Floatx:CLIP OFF
3210   Labl=OROUND(Labl,2)
3220   LABEL USING "*,K":Labl
3230   CLIP ON
3240   PENUP
3250 Xticmark:MOVE Majpos,Cymin
3260   IF Xtic=0 THEN IORAW 0,Xtictlen
3270   IF (Minor=0) OR (Majtic=Xmajor) THEN GOTO No_xminor
3280   Mininc=Tickspace/(Minor-1)
3290   IF Xlog THEN Mininc=(10^(Majpos+Tickspace/-10^Majpos))/(Minor-1)
3300   FOR Mintic=1 TO Minor
3310     Minpos=Majpos+Mininc*Mintic
3320     IF Xlog THEN Minpos=LGT(10^Majpos+Mininc*Mintic)
3330     MOVE Minpos,Cymin
3340     IORAW 0,Xtictlen/2
3350   NEXT Mintic
3360 No_xminor: NEXT Majtic
3370 LOIR 0
3380 LOG 4
3390 MOVE (Xlower+Xupper)/2,Ylower
3400 CLIP OFF
3410 LABEL USING "*,K":Xs
3420 CLIP ON
3430 PENUP
3440 Y_axis: IF Ymajor=0 THEN GOTO Dataplot
3450 Minor=INT((10*(ABS(Ytic)-Ymajor))
3460 Tickspace=Cymax-Cymin
3470 IF Ymajor>1 THEN Tickspace=(Cymax-Cymin)/(Ymajor-1)
3480 MOVE Cxmin,Cymin
3490 DRAW Cxmin,Cymax
3500 LOG 8
3510 LOIR 0
3520 FOR Majtic=1 TO Ymajor
3530   Majpos=Cymin+Tickspace*(Majtic-1)
3540   MOVE Cxmin-Ytictlen,Majpos
3550   Labl=Majpos
3560   IF Ylog THEN Labl=10^Majpos
3570   IF ((ABS(Labl))>=1.E+6) OR (ABS(Labl)<1.E-4) AND (Labl<>0) THEN GOTO F1
oaty
3580   IF Labl<>0 THEN
3590     Temp=-INT(LGT(ABS(Labl)))-1
3600     IF Temp<=0 THEN Temp=0
3610     Labl=OROUND(Labl,7-Temp)
3620   END IF

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

```

3630 CLIP OFF
3640 LABEL USING "*,K":Labl
3650 CLIP ON
3660 PENUP
3670 GOTO Yticmark
3680 Floaty: CLIP OFF
3690 Labl=ROUND(Lab1,2)
3700 LABEL USING "*,K":Labl
3710 CLIP ON
3720 PENUP
3730 Yticmark: MOVE Cxmin,Majpos
3740 IF Ytic>0 THEN IDRAW Yticlen,0
3750 IF (Minor=0) OR (Majtic=Major) THEN GOTO No_yminor
3760 Mininc=Tickspace/(Minor+1)
3770 IF Ylog THEN Mininc=(10*(Majpos+Tickspace)-10*Majpos)/(Minor+1)
3780 FOR Mintic=1 TO Minor
3790 Minpos=Majpos+Mininc*Mintic
3800 IF Ylog THEN Minpos=LG(10*Majpos+Mininc*Mintic)
3810 MOVE Cxmin,Minpos
3820 IDRAW Yticlen/2,0
3830 NEXT Mintic
3840 No_yminor: NEXT Majtic
3850 LDIR 90
3860 LORG 5
3870 MOVE Xlower,(Ylower+Yupper)/2
3880 CLIP OFF
3890 LABEL USING "*,K":ys
3900 CLIP ON
3910 PENUP
3920 Dataplot: LDIR 0
3930 IF N1=0 THEN GOTO Titleplot
3940 LORG 5
3950 Penc=-2
3960 FOR Pointr=1 TO N1
3970 Xx=X(Pointr)
3980 IF Xlog THEN Xx=LG(X(Pointr))
3990 Yy=Y(Pointr)
4000 IF Ylog THEN Yy=LG(Y(Pointr))
4010 IF Penc=-2 THEN MOVE Xx,Yy
4020 IF Penc=-1 THEN DRAW Xx,Yy
4030 IF N<0 THEN
4040 CLIP OFF
4050 LABEL USING "*,K":*
4060 CLIP ON
4070 PENUP
4080 END IF
4090 Penc=-1-(N<0)
4100 NEXT Pointr
4110 Titleplot: LORG 5
4120 MOVE (Xlower+Xupper)/2,Yupper
4130 CLIP OFF
4140 LABEL USING "*,K":Title$
4150 CLIP ON
4160 PENUP
4160 SUBEND

```

Figure 69. Computer Program to Reduce Creep Data, Plot Creep Rate Curves and Print Data Tables (Continued)

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